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RESEARCH MEMORANDUM

STATISTICAL APPROACH TO THE ESTIMATION OF LOADS AND PRESSURES ON SEAPLANE HULLS FOR ROUTINE OPERATIONS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
March 27, 1957

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STATISTICAL APPROACH TO THE ESTIMATION OF LOADS AND PRESSURES ON SEAPLANE HULLS FOR ROUTINE OPERATIONS

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SUMMARY

Available measurements of the seaway conditions expected during seaplane operations are combined with experimental data on the impact loads experienced during full-scale and model tests in order to estimate the repeated loadings of seaplanes for long operating periods. Although the accuracy of the results cannot be substantiated by operational data, the nature of the variations that might be expected in the magnitude and frequencies of the seaplane loads and hull pressures for several assumed operations was reflected in the estimated results. These results indicated that the low landing speeds for antisubmarine-warfare seaplanes reduced the magnitude of the loads but that the more frequent landings and take-offs required for these operations greatly increased the total number of loads. The results also indicated that increased operations from the open ocean for a given seaplane type may have a relatively small effect on the magnitude of the loads or pressures.

INTRODUCTION

The loads developed on seaplane hulls during landings and take-offs depend upon a number of seaplane and operating factors such as hull configuration, descent speed, and sea condition. The effect of these different factors on the loads or hull pressures has been studied in the past by model and full-scale tests under controlled conditions, and the results, such as those reported in references 1 to 7, have provided the basis for present methods for specifying maximum design loads.

With the recent application of seaplanes to newer and extended types of operations such as the antisubmarine warfare services, attention has been centered not only in the maximum loads but also in some of the more detailed characteristics of the load history. For example, information

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on the many loading cycles experienced in these specialized operations is of interest in fatigue studies. These studies, however, have been hindered by lack of information on the number of the different loads expected over long operating periods for various services.

The purpose of the present report is to provide a basis for estimating from available test data the frequencies and intensities of seaplane loads and hull pressures for given operations. Inasmuch as the loads and pressures are influenced by a number of seaplane and operating factors, it is first necessary to generalize from test data the significant effects of these factors on the loads for conditions of continuous random waves. The results are then used to provide estimates of the load histories for several routine operations in various sea conditions. The load histories for the different seaplane utilizations are then compared to indicate the variations that might be expected and some of the major factors which cause these variations.

SYMBOLS

c wave propagation velocity, knots

h wave height, ft

λ wave length, crest to crest, ft

n normal acceleration, from 1 g steady-state condition, g units

H significant wave height, defined as the average value of the one-third highest waves for a given period of time, ft

V velocity, knots

$P^*(h)$ probability of exceeding a wave height for a given sea condition

$P(h)$ probability distribution of wave height for a given sea condition

$P(n)$ probability distribution of normal acceleration

$\overline{h^2}$ mean-square wave height

ρ density, slugs/cu ft

g acceleration due to gravity, ft/sec^2

Subscripts:

L landing speed

R relative velocity

GENERAL CONSIDERATIONS AND METHOD

During each landing and take-off, the seaplane experiences several impacts of varying intensities depending on a number of factors such as wave height and slope, operating speed, and seaplane-hull configuration. An example of the accelerations which occur for a seaplane landing in 4-foot waves at a landing speed of 70 knots is given in figure 1. As may be noted in this time history, the largest load does not generally occur during the first impact but during some subsequent impact. These results indicate that conditions prior to landing are not necessarily a good index of the load intensities but rather that the load histories depend more on the uncontrolled conditions which develop after the initial impact. It thus seems apparent that data obtained under controlled conditions for single impacts may not alone serve as a reliable indication of the number and intensity of all loads for given landings.

For extended operations of a given seaplane, the total load history consists of a number of landings and take-offs, of the type illustrated in figure 1, for different wave conditions. The estimation of the total load history for the seaplane requires the integration of the loads for all landings and take-offs for the period of operation being considered. Inasmuch as data are not available for separate landings under a wide variety of sea conditions and for different seaplane types, it is accordingly necessary to estimate from available information the influences of the sea and seaplane parameters on the loads so that existing time-history data of the type given in figure 1 may be modified in order to estimate the loads for landings in other sea conditions. The estimated number and intensity of the loads for given landings in different sea conditions may then be simply summed to arrive at the overall load history.

For the present purpose of describing the reactions of a seaplane in terms of applied loads or pressures, the magnitude and frequency of the normal accelerations, the maximum pressures on the hull, the average pressure and the wetted area are used. The normal accelerations are a measure of the forces of interest in considering the overall strength of the seaplane structure, whereas the pressures and wetted area determine the local and total forces on the hull bottom which, in turn, define the strength requirements for the hull.

Significant Parameters

The number and magnitude of the loads imposed on seaplane hulls during landings and take-offs have been found from past experience to depend on the following sea and seaplane parameters:

(a) Hull or float configuration such as plan form, longitudinal shape, and transverse shape

(b) Beam-loading coefficient which depends on the weight of the seaplane and hull size

(c) Landing approach or take-off conditions which are normally defined by the angle of the keel to the water surface (trim angle), airplane attitude, and the velocity of the seaplane either in reference to the water or other appropriate reference

(d) Seaway conditions such as the wave slope, wave propagation velocity, and the orbital velocity, although the slope and velocity vectors are normally used in calculating the loads

(e) Aerodynamic lift which influences the seaplane sinking speed or vertical velocity

(f) Piloting technique which would be expected to influence the operational parameters and these, in turn, affect the seaplane reactions

As will be discussed later, no simple method appeared available to account for the effect of all these variables on the loads or hull pressures. It appeared, however, that the predominating influences could be established to afford a basis for estimating, at least, the general level of the loads and pressures and the frequencies of occurrence for different operations.

Method

The general method developed in this paper for estimating the loads or pressures is illustrated in figure 2. A step-by-step example of the calculations involved in estimating an acceleration history is given in appendix A.

The distribution of wave heights for a given operation over a long period of time such as a year is presented in figure 2(a) and the distributions of normal accelerations which would be expected for a given seaplane landing in waves of constant height are given in figure 2(b). From known or assumed lengths of take-off and landing runs and the total number of flights, the distance that the seaplane travels on the waves in given wave heights may be determined. These distances, when divided by an average wave length for the appropriate wave height, give an estimate of the number of impacts on waves of a given height. Multiplying the appropriate distributions of accelerations in figure 2(b) by the total number of impacts for the corresponding wave height yields a family of curves which, when summed, give the total acceleration history shown in figure 2(c).

AVAILABLE TIME-HISTORY MEASUREMENTS OF SEAPLANE ACCELERATIONS AND HULL PRESSURES

The available time-history data on the seaplane accelerations and hull pressures which form the basis for the present study consist of full-scale- and model-test results obtained from investigations conducted at the Langley Aeronautical Laboratory of the National Advisory Committee for Aeronautics. These data are described in the following sections.

Normal Accelerations

Measurements of the normal accelerations experienced during landings in given wave conditions were obtained from model tests in the seaplane tanks at the Langley Laboratory. The model characteristics and test conditions (full-scale values) were as follows:

	Model		
	A	B	C
Landing speed, knots . . .	70	100	120
Wing loading, lb/ft^2 . . .	40	80	120
Angle of dead rise, deg . .	20	20	20
Length-beam ratio	15	15	15
Weight, lb	75,000	75,000	75,000

The corresponding full-scale values of the hull beam and forebody length of the models were 5 feet 10 inches and 50 feet 5 inches, respectively. The hull had horizontal chine flare and a basic angle of dead rise of 20°. Both the dead-rise angle and the chine flare were constant for a distance of 21 feet forward of the step. The beam was also constant over this distance. The dead-rise angle then increased to 68° at the forward perpendicular while the beam decreased.

Time histories of normal acceleration were available from about 60 to 160 landings of the seaplane models for the test conditions summarized in the preceding table for both 2-foot and 4-foot wave heights (full-scale values). An inspection of these results indicated, however, that only the 4-foot-wave conditions were representative of the wave height-length ratios h/λ which occur in routine operations. Only the data for the 4-foot-wave conditions were, therefore, used in the present analysis. The sample time history of the normal accelerations given in figure 1 was obtained in a landing run for one of these tests.

In order to obtain a simple description of the acceleration data in figure 1 for the different landing speeds, the acceleration value corresponding to each impact was read from the time histories and classified by acceleration intervals of 0.5g for each landing speed. The results are given in the form of probability distributions for the three landing speeds in figure 3. These distributions are used subsequently to estimate the normal accelerations for other wave heights and landing speeds.

Hull Pressures and Wetted Areas

Measurements of the hull pressures and wetted areas were obtained from full-scale tests during 64 landings and take-offs of a seaplane in wave heights up to about $2\frac{1}{2}$ feet. The test conditions varied from normal landings to stalled landings with flap settings varying from zero to full flaps. The general characteristics of the seaplane and the test conditions are as follows:

Landing speed, knots	66
Wing loading, lb/ft^2	40
Angle of dead rise, deg	$22\frac{1}{2}$
Length-beam ratio	6
Operating weight, lb	41,000

The full-scale seaplane had a beam of 10 feet and an overall forebody length of 30 feet. The hull had horizontal chine flare and a basic angle of dead rise of $22\frac{1}{2}^{\circ}$. The angle of dead rise, the chine flare, and the beam dimensions were constant for a distance of approximately 10 feet forward of the step. For the balance of the hull to the forward perpendicular, the dead-rise angle increased to approximately 75°.

From time histories of pressure measurements taken on the hull bottom of the seaplane, data were obtained of the maximum pressure near the step, the average pressures over the wetted areas, and the wetted hull lengths or areas for landings and take-offs in smooth water and $2\frac{1}{2}$- foot waves.

Probability distributions were obtained from these data in a manner similar to that previously described for the model acceleration measurements. The results are given in figures 4, 5, and 6 for the maximum pressure, average pressures, and wetted keel lengths, respectively. It may be noted that the curve faired through the maximum pressure data in figure 4 does not follow the data points for the higher pressures since it was considered that some of the landings were considerably more severe than would be expected in routine operations for the same number of landings. The faired curve in the figure is therefore dashed at the higher values to indicate the estimated pressures for normal conditions.

ESTIMATES OF THE INFLUENCE OF SEAPLANE AND SEA PARAMETERS ON ACCELERATIONS AND PRESSURES

The success that can be achieved in estimating the loads and pressures for extended operations depends on the success obtained in accounting for the effects of the different seaplane and sea parameters on the basic results given in figures 3 to 6. In this section, the available information on the effects of these parameters on the loads is considered. From these considerations of both single parameters or groups of parameters, rather simple adjustments to the load histories seem to be suggested as a means of estimating the significant variations in the loads for different operations.

Seaplane-Hull Characteristics

Test results have indicated that variations in the seaplane-hull characteristics, such as angle of dead rise, length-beam ratio, or beam loading, have substantial effects on the loads or pressures developed on the seaplane hull in various wave heights (see refs. 4 to 7). An examination of the results available, however, indicated that the individual effects of changes in the hull configuration on the loads could be approximated by an appropriate factor. Reference 4, for example, indicates that the accelerations and pressures vary approximately as follows for given wave heights but different degrees of dead-rise angle:

Dead-rise angle, deg	Acceleration (percent of 20° dead-rise angle)
20	100
40	71
60	43

Similarly, reference 6 indicates that the vertical accelerations for given wave lengths increase by a factor of about 2 when the length-beam ratio is changed from 20 to 6. For the present study, it was therefore assumed that simple adjustments of the load or pressure histories on the basis of these results would be adequate to account for variations in hull configurations.

Operational Parameters

A number of variables which influence the loads, such as trim angle, forward and sinking speed, and flight attitude at time of landing, may be grouped under operational parameters. Although considerable work has been done in the past to define the effect of these variables on the loads (refs. 2 and 3), no simple methods for applying the results directly to the problem of estimating the loads and pressures for routine operations were evident. For example, the available data on the effect of trim angle on the loads generally represent fixed trim conditions, such as a trim angle of 3°. Discussions with pilots have indicated, however, that variations of at least $\pm 2^{\circ}$ from the desired trim angle would be expected at the time of the initial impact for a given landing. In addition, only little control is had over the trim angle for subsequent impacts, and considerable more trim-angle variations would be expected for the balance of the landing run. No simple correction would appear to account for these trim-angle effects. Data obtained from tests of a full-scale seaplane were examined for the relationship between acceleration and sinking speed; the results are given in figure 7. In this figure, the variation of acceleration with initial sinking speed is shown for the successive impacts for 20 landings in approximately $2\frac{1}{2}$-foot waves. It is evident from the scatter of points in figure 7 that the initial sinking speed by itself is not simply related to the magnitude of the acceleration, even for a given seaplane and for a given sea condition.

Although it seemed impracticable to account for the individual effects of trim angle, sinking speed, or seaplane attitude on the loads for routine operating conditions, a further consideration of the data from the full-scale- and model-seaplane tests indicated that the overall effects of these variables were included in the acceleration and pressure data of figures 3 to 6. It also appeared that these variables would have similar effects on other seaplane operations. No further adjustments of the basic distributions in figures 3 to 6 for the separate effects of trim angle, sinking speed, or flight attitude were, therefore, considered necessary.

Flight speed has a marked influence on the magnitude of the loads and pressures for individual wave impacts. Both theoretical and experimental data indicate that the load varies as V^2 for geometrically similar impacts (refs. 2 and 3). For operations of different seaplanes in different sea conditions, however, geometrical similarity is not obtained between the impacts for each operation, and under conditions which included both smooth- and rough-water landings, the accelerations have been found to increase with landing speed at rates varying between V and V^2. For rough-water landings, in which at least the initial impact usually occurs on the forward slope of the wave, a high rate of increase of the load with landing speed appears to result from the increased velocity of the hull penetration into the wave due to the component of seaplane velocity normal to the wave front. A sufficient number of tests has not been made to establish an average or representative relation between the loads or pressures and the horizontal speed for all impacts of routine operations in different wave conditions. An inspection of the model test data in figure 3 indicates that the accelerations increase approximately as $V^{1.3}$ for landings in 4-foot waves. Although this value may not apply to all operations in other wave conditions, it is used here as the basic relation between seaplane speed and the accelerations or pressures for different seaplane utilizations. Some modification will be made to this relation later to account further for differences in sea conditions.

Seaway Parameters

The seaway parameters normally required in the analysis of the loads and motions of a seaplane are the wave slopes, wave propagation velocity, and the orbital velocity of the water particles. There is insufficient information in the literature on sea conditions (refs. 8 to 11, for example) to define simply these three quantities. It is necessary, therefore, to determine some parameter which may be used to approximate the influence of the sea condition on the seaplane loads. Since it was indicated in the previous section that the loads varied as a function of V (in this analysis V is taken as the landing speed), it was considered that some modification to the value of the landing speed could be used to include the influence of the sea condition. The general procedure to follow was indicated from an inspection of the data on normal acceleration for different wave heights which showed that the magnitude of the accelerations increased with wave height. It is also known that the propagation velocity increases with wave height for given values of slope due to the increased wave length (ref. 8). It appeared, therefore, that the increase in normal acceleration could be related to the wave propagation velocity to account for variations in wave height.

In order to relate the wave propagation velocity to the loads and pressures, it is first necessary to determine the distribution of wave heights and the range of wave slopes. From this information, the wave lengths and then the propagation velocities may be computed, since this velocity is related directly to the wave length.

Wave heights.- Considerable information is available on the conditions of the sea in the form of statistics on significant wave heights which designate the average height of the highest one-third of the waves for a given period of time (see, for example, refs. 8 to 11). Separate samples of these data when summarized as probability distributions (fig. 8) appear to fall roughly into three groups which represent the sea conditions in "sheltered areas," "lee side of islands," and the "open ocean." Sheltered areas as used here represent lakes and nearly landlocked bays which are protected from the large waves and swells generated in the open sea. Lee side of islands refers to water in airdromes at island bases or to bays which are relatively open to the effect of waves from the open ocean. The open ocean is, as the term implies, water of the oceans away from any sheltered area. In order to obtain an indication of the average conditions which might represent each group of data in figure 8, an average curve was faired through the different sets of probability distributions of significant wave heights in the figure.

In order to apply these data on significant wave heights to the problem of estimating the hull loads or pressures arising from all landing or take-off impacts, it is necessary to convert the results given by the average curves in figure 8 to a form giving the more detailed information on the distributions for all wave heights. The method for using the data on significant wave heights to approximate the distributions of all wave heights is described in appendix B. Briefly, the method involves first estimating the distributions of the root-mean-square values of wave heights from the data in figure 8 and then transforming these distributions to distributions of the heights of all waves. The results are given in figure 9.

Wave slope and propagation velocity.- The information in reference 8 indicated that a wave height-length ratio of 1:7 is a theoretical limit to the steepness of a wave after which the wave would break. Since the wave characteristics depend on the wind velocity, length of open area or fetch, and the duration of the wind, the waves go through a cycle of buildup and decay. During these cycles, the h/λ values may vary over a range of 1:7 to about 1:120 with a probable range of 1:20 to 1:100.

If two waves exist, both having an h/λ of 1/40 but the waves are 1 foot and 20 feet high, the wave lengths would be 40 feet and 800 feet, respectively. The propagation velocity for these two waves would be 8.5 knots and 38.0 knots as computed by the formula for trochiodal waves (ref. 8)

$$c = \frac{1}{1.69}\sqrt{\frac{g}{2\pi}\lambda} = 1.34\sqrt{\lambda}$$

where

c wave propagation velocity, knots

λ wave length, ft

In order to account for the effect of this increased wave propagation velocity for increased wave heights on the loads or pressures, the propagation velocity was added to the landing or take-off speed to obtain the relative speed between the seaplane and the waves at time of impact. For a given seaplane it was further considered that the impacts are geometrically similar. For this condition, the accelerations would be proportional to V^2 where, as has just been noted, V is equal to the sum of the seaplane speed and the wave propagation velocity, or

$$n \propto \left(V_L + c\right)^2$$

The data from models A, B, and C were considered in determining whether this relation could be used in approximating available data. The comparison was limited in nature since data for only 2- and 4-foot waves were available and the h/λ values for the two wave heights covered a different range with only a small sample in a comparable range. The data indicated that the foregoing relation roughly approximated the data. The relation was used, therefore, and assumed to be sufficiently representative to be extended to 40-foot wave heights.

Since a range of wave height-length ratios exists in the different sea conditions, this same range must be considered in obtaining an average speed of wave propagation. The range of height-length ratios considered are 1:20 to 1:100 as shown in table I. This table gives the wave lengths and the propagation velocities for different wave heights and h/λ ratios. The velocities were computed by the formula given previously.

It may be noted that several values of wave lengths and propagation velocities are omitted from table I for the higher and longer waves. These omissions were made for two reasons. First, high waves with long wave lengths seldom occur. Second, discussions with pilots indicated that landings would normally be made parallel to the wave crests when the wave lengths become several times the span of the seaplane. Since the seaplanes under consideration were of the bomber or transport types with relatively large wing spans, the wave lengths of 300 feet or more for the smaller wave heights and progressively longer waves for the higher wave heights were omitted. The table contains, therefore, only the values of wave lengths for the different wave heights which are considered in this analysis.

The propagation velocities listed in the lower half of the table were averaged to give the average propagation velocity for the different wave heights. These average velocities were added to the landing speeds and plotted against wave heights in figure 10 to obtain the relative velocity in knots. It may be noted from figure 10 that the relative velocity increases rapidly with wave height up to a height of 15 or 20 feet. Because of the omission of the longer wave lengths for the higher waves, the relative velocity then increases at a much lower rate.

The distribution of normal accelerations for a given landing speed and wave height may then be modified for other wave heights by the relation

$$P(n) \propto \left(V_L + c\right)^2$$

or

$$P(n) \propto {V_R}^2$$

where the subscript R refers to relative velocity. If the distribution for 4-foot waves is considered as the basic distribution of accelerations, the distribution for 8-foot waves, for instance, can be calculated by the relation for given probability levels

$$P\left(n_8\right) = P\left(n_4\right) \frac{{V_{R_8}}^2}{{V_{R_4}}^2}$$

where the numbers used as subscripts designate the wave heights. This procedure was used to obtain the distributions of accelerations for the different wave heights shown in figure 11.

SUMMARY OF CONDITIONS AND ASSUMPTIONS

The following conditions or assumptions were introduced or discussed in the preceding section and are used in the subsequent analysis:

(a) Data from the full-scale seaplane and the seaplane models on normal accelerations, local pressures, wetted area, and average pressures are considered comparable to data expected from routine operations under similar seaplane and seaway conditions.

(b) The effects of operational parameters such as trim angle, sinking speed, and flight attitude are included in the basic distributions and it is assumed that these variables will have similar effects for other seaplane operations and seaway conditions.

(c) The effect of airspeed on the loads may vary for different landing speeds and operations from V to V^2. In this analysis, the effect of landing speed is taken as approximately $V^{1.3}$ as shown by the data from the model tests.

(d) Distributions of loads for different seaplane-hull configurations may be accomplished by adjusting the magnitude of the loads by an appropriate factor determined from research on the effect of the parameters.

(e) The wave heights are assumed to be a Gaussian distribution with a narrow spectrum and the distribution of wave heights is given by (see eq. (11), appendix B)

$$Q(h) = \int_0^\infty \frac{2y}{\overline{y^2}} e^{-\frac{h^2}{y^2} - \frac{y^2}{\overline{y^2}}} dy$$

(f) The effect of the sea parameters may be represented by an increase in landing speed so that $n \propto {V_R}^2$ where V_R is equal to the landing speed of the seaplane plus the average speed of propagation of the waves for a given wave height.

(g) The wave height-length ratios of importance are from 1:20 to 1:100.

(h) The seaplane is landed into the waves except when the wave length is several times the wing span. For the long-wave conditions, the seaplane is landed parallel to the wave crests.

(i) The effect of wind on the landing speed is neglected.

ESTIMATION OF LOAD AND PRESSURE HISTORIES

Estimation of Distribution of Accelerations for Assumed Operations

In order to estimate the total load histories, the method for calculating the accelerations as described for figure 2 was applied to several assumed operations. Table II gives the types of airplanes, length of mission assumed, range in speed, angle of dead rise, and sea conditions investigated. The loads on the patrol bomber and the supersonic bomber were investigated for landing speeds of 70 and 120 knots, angles of dead rise of 20° and 40°, and sea conditions which varied from 50 percent of the landings in the open ocean to as little as 0.01 percent. This latter condition may be classed as an emergency condition rather than a design condition. The landing speeds of the antisubmarine-warfare (ASW) seaplane are 40 and 80 knots, and 90 percent of the operations were assumed to occur in the open ocean.

In addition, it was assumed that each seaplane would operate for 1,000 flight hours and those seaplanes landing at 70 knots, 120 knots, 40 knots (ASW), and 80 knots (ASW) would require, for each combined take-off and landing, a distance of 10,000, 13,000, 4,000, and 6,000 feet, respectively. It was also assumed that the ASW seaplane made 20 to 30 landings per mission, whereas the other seaplane types made only one landing per mission.

The estimated load histories for several of these operations are given in figure 12 as the cumulative frequency distributions of acceleration. An illustrative example of the procedure for estimating the load history is given in appendix A for operation A of table II for 70 knots landing speed, 20° angle of dead rise, and a mission length of 11 hours.

Estimation of Maximum Pressure Histories

The procedure for estimating the distribution of the maximum or local pressures follows the identical steps used in estimating the acceleration histories once the distributions of pressures for different wave heights and landing speeds are determined. In this case, the pressure distribution obtained from flight tests of the XPBS-1 seaplane (fig. 4) was used as a basic distribution for a wave height of 2 feet. This distribution is plotted as the curve for 2-foot waves of figure 13. The distribution of pressures for the other wave heights shown in the figure was obtained from this distribution by assuming that for a given seaplane the pressures varied as the velocity squared, where again it is assumed that the velocity is the relative velocity between the seaplane and the wave. It should be noted that the pressure does not vary exactly as the accelerations, but it was felt that the same relations could be used as a first approximation.

The estimated cumulative frequency distributions of maximum pressures near the step for 1,000 flight hours of the operations listed in table II for landing speeds of 70 knots (40 knots for the ASW airplane) and 20° dead-rise angle are given in figure 14.

Local Pressures at a Location Forward of the Step

In considering the probability distribution of maximum pressures at a point forward of the step, it is necessary to know the variation or change in the pressure as maximum pressure moves forward with wetted area and the probability that the point under consideration will be wetted during an impact. The variation of the pressure as the wetted area moves forward is shown in figure 15 as the ratio of the maximum pressure at a given point on the keel to the maximum pressure at the step. This curve is based on pressure data obtained on models in the Langley impact basin (ref. 12) and checked by a limited amount of flight data. Figure 15 indicates that the peak pressures at a point, say 25 percent of the keel length forward of the step, would only be about 35 percent of the magnitude of the peak pressures at the step. The frequency of these loads depends, however, on the probability of this location being wetted.

The probability of wetting different keel lengths of the XPBS-1 seaplane during landings in smooth water and in $2\frac{1}{2}$-foot waves was given in figure 6. Since no additional data were available for the higher wave heights, three additional curves were estimated for 5-, 10-, and 20-foot waves and are shown as dashed curves in figure 6. These last three curves are considered to be only very rough estimates based on the judgment of engineers who have conducted flight tests of seaplanes.

The following procedure was used to estimate the distribution of local pressures at a point forward of the step, say at 25 percent of the keel length. The distributions of maximum pressure for different wave heights (fig. 13) were modified by the value obtained from figure 15 to account for the decrease in pressure forward of the step. The probability value for each curve as obtained in the preceding step was then modified by the appropriate value from the curves in figure 6 to represent the distribution at the point under consideration. The resulting curves were then multiplied by the number of impacts expected in each wave height and summed to obtain the total distribution. The results are shown in figure 16. The distribution of maximum pressures at the step for operation A at 70 knots and 20° angle of dead rise is included in figure 16 for comparison.

Estimation of Total Pressures or Forces

The total pressure or force on the hull is the product of the average pressure and the wetted area. The data in figure 5 indicated that the average pressures fell roughly into three groups depending upon the extent of the wetted area. Average curves for the pressures for wetted areas of 0 to 13 percent, 13 to 40 percent, and over 40 percent of the forebody were given in figure 5. These data are for operations in smooth water and up to $2\frac{1}{2}$-foot waves for a seaplane having approximately 20° angle of dead rise and an average landing speed of 66 knots. For greater wave heights, it was assumed, as in the case of the acceleration, that the pressures would increase in proportion to the square of the relative velocity. From a knowledge of the average wave lengths, the distance traveled through these wave lengths, and the probability of wetting given areas or keel lengths from figure 6, a curve may be derived by following the procedures noted in the previous section to give the total pressure on the hull. The results for four operations are given in figure 17.

DISCUSSION

Limitations

The data available for the present study were obtained from tests in which the models or seaplanes reduced speed during landing by action of the drag forces. The rate of deceleration for the model with a landing speed of 120 knots was approximately 1.25 times the rate of deceleration for the model with a 70-knot landing speed. The higher rate of deceleration would presumably reduce the intensity of the loads for the later impacts. Some further modification might be needed when the present data are applied to seaplanes which decelerate quickly, such as those with reversible propellers. It appears, at the present time, that any modification to the present data would at least consist of reducing the number of accelerations to account for the reduced landing distance.

In regard to the pressure data, there is the possibility that the basic distributions of maximum pressures (fig. 4) and the variation of the maximum pressure as it moves forward (fig. 15) may not be as well defined as the distributions of accelerations. These pressure data were obtained on seaplanes or test models where it was assured that a step landing was made. It is possible, however, that some impacts for routine operations, especially in the larger wave heights, may occur bow first or with the keel parallel to the wave slope. The effect of inadvertent impacts of these types on the distribution of the maximum pressure at the step or at a point forward of the step is not known at this time.

Comparison of Distributions of Normal Accelerations

An inspection of the distributions of normal acceleration given in figure 12 for some of the operations listed in table II indicate several interesting and probably unexpected results. The curves representing the four operations with landing speeds of 70 knots and 20° angle of dead rise are very similar although the operations varied from 0.01 percent of the landings in the open ocean to 50 percent of the landings in the open ocean. For the landings in the open ocean, the large wave heights that might be encountered (see fig. 9) would be expected to produce rather severe loads. Severe loads are not indicated in figure 12, however, for two reasons. First, it was previously assumed that, because of the long wave lengths associated with the high waves, landings would generally be parallel to the wave crest. This assumption tends to eliminate from the present analysis the infrequent large waves which might be expected in the open ocean. As has been previously noted in figure 10, the effect of omitting these high waves is to reduce the rate at which the relative velocity V_R increases for waves above 15 to 20 feet. Since the accelerations are scaled in proportion to the square of the relative velocities, the loads would increase slowly for wave heights greater than 20 feet. Second, 25 to 50 percent of the landings for these four operations were assumed to occur in the lee side of islands. Wave heights up to 15 or 20 feet may occur in these sea conditions and would produce most of the large loads experienced in each operation. On the basis of these results in figure 12, it would appear that operations in various combinations of seaway conditions would have only a limited effect on the load histories of similar seaplane types.

The curves for operation A with a landing speed of 120 knots (fig. 12) indicate an appreciable increase in the magnitude of the loads at a given frequency as compared with operation A with a landing speed of 70 knots. For example, 100 accelerations of 4.2g or greater would be experienced for operation A (70 knots), whereas 100 accelerations of 7.7g or greater would be experienced for operation A (120 knots). This increase in the magnitude of the loads by a factor of 1.8 indicates that the seaplane landing speed has a significant effect on the load histories.

A comparison of the load history for the antisubmarine-warfare seaplane with the other load histories in figure 12 shows the combined effect of the reduced landing speed and the frequent take-offs and landings for the ASW type of operation. The lower speed reduces the magnitude of the loads. The increased number of landings in 1,000 hours of operation, however, increases the total number of loads to such an extent that a seaplane in this type of operation might be expected to experience a fatigue failure.

A comparison of the distributions of normal accelerations for operations A in figure 12 for 20° and 40° dead-rise angles illustrates the effect of the change in dead-rise angle on the loads. The magnitude of the accelerations for the seaplane with 40° angle of dead rise has been reduced to approximately 70 percent of the values for the seaplane with 20° angle of dead rise.

Comparison of Distributions of Hull Pressures

The distributions of hull pressures in figures 14, 16, and 17 follow the same general trends for the different operations as has been noted for the accelerations. The influence of both the reduced pressures forward of the step and the lower probability of wetting a point forward of the step in a given impact is reflected by the reduced pressures and frequencies of figure 16 as compared with those of figure 14. It is noted that the percent of wetted area has already been taken into account in defining the average hull pressures in figure 17. For other operations in which the seaplanes may have different forebody areas, the curves in figure 17 would be shifted upwards or downwards in proportion to the ratio of the forebody areas.

CONCLUDING REMARKS

Estimates have been made of the frequencies and intensities of seaplane normal accelerations and hull pressures for different operations by use of procedures in which the effect of many of the parameters which influence the seaplane response were included statistically in the available test data. Although data are not available from service operations to check the results obtained, the tendencies noted in the estimated load histories for different seaplane utilizations appear reasonable. The effects of increased landing and take-off speeds for different operations were reflected in increases in both the number and magnitude of the loads. The lower landing speed for antisubmarine-warfare seaplanes tended to reduce the magnitude of the maximum loads, but the more frequent landings expected for this type of service increased the total number of loads to such an extent that fatigue failures may be expected. It also appeared that an increased frequency of operation from the open ocean for similar types of seaplanes may have a relatively small effect on the magnitude of the loads and pressures.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 26, 1956.

APPENDIX A

SAMPLE CALCULATIONS

The procedure and calculations for estimating the normal accelerations for the patrol bomber for operations A with a 20° dead-rise angle, a landing speed of 70 knots, and a length of mission of 11 hours is worked out step by step in the following paragraphs as an illustrative example. From table II, 25 percent of the landings are in sheltered areas, 25 percent are in lee side of islands, and 50 percent are in the open ocean. These percentages and the curves of figure 9 must be used in combination to obtain the distribution of wave heights for this type of operation and presumably for a relatively long period of time. In this example, 1,000 hours will be assumed.

The total distribution of wave heights for this distribution is obtained in the following steps and presented in table III. The probability of equalling or exceeding given wave heights are obtained from the figures for each sea condition for the same wave heights such as 0, 2, 4, 6, etc. These values of probability are given in columns (1), (2), and (3) of table III. Next, the probabilities in each column are multiplied by the proportion of landings in each sea condition, 0.25, 0.25, and 0.50 for the sheltered area, lee side of island, and the open ocean, respectively. These adjusted probabilities are given in columns (4), (5), and (6) of the table. Adding these three columns yields the total distributions given in column (7); the data in columns (4) to (7) are plotted in figure 18.

In relating the behavior of the seaplane to the wave heights, the information given in figure 11 for the distribution of accelerations for given wave heights is used. Since it is impractical to have an infinite number of curves in this figure for all finite wave heights, it must be assumed that the curve for 2-foot waves describes the distribution of accelerations in wave heights from 0 to 3 feet, the 4-foot curve for 3- to 5-foot waves, the 6-foot curve for 5- to 7-foot waves, etc. It is necessary, therefore, to calculate the proportions of the distribution of wave heights given in figure 18 that fall into each of the brackets. This calculation is presented in table IV; the procedure is as follows:

The probability for the upper and lower limit of each bracket is determined from figure 18 and given in column (1) of table IV. Successive subtraction of the probabilities gives the proportion of the waves (column (2)) in the brackets of wave heights (column (3)) with an approximate mean wave height for the bracket (column (4)). These mean values of wave heights should correspond to the wave heights in figure 11. It should be noted that column (2) totals 1.00.

The probability distributions of acceleration for the 2-, 4-, 6-, etc., foot waves are obtained from figure 11 and given in table V(a). Each of these curves, however, represent the distribution of accelerations if all landings were made in a given wave height. These probabilities must be modified by the proportion of landings in each wave height for this operation as was determined in table IV (column (2)). These calculations are performed in table V(b). Summing columns (1) to (9) of table V(b) gives the probability distribution (column (10)) of the accelerations for the total operation.

In order to convert the probability distribution to a cumulative frequency distribution, that is, the number of accelerations greater than a given value, the distance traveled on the water and the wave lengths must be considered. It was previously assumed that 1,000 flight hours would be considered and 10,000 feet would be traveled on the water for each take-off and landing. If the average length of flight (11 hours) is used, 91 flights would be made and 910,000 feet would be traveled on the water. (This distance assumed speeds above the "hump" speed of the seaplane). This distance is subdivided into distance traveled in wave heights within given brackets in column (1) of table VI. In order to determine the number of impacts (if it is assumed that each wave causes an impact), the distances must be divided by the average wave length (column (2)) for the wave height brackets used in the table. These averages are determined from information such as given in table I. The number of impacts by wave heights are given in column (3). The total of these impacts gives the number 7,414 expected in 1,000 hours of flight for this operation.

The product of the total number of impacts (total of column (3) in table VI) and the probabilities in column (10) of table V(b) is the cumulative frequency distribution of normal acceleration expected for the conditions specified and is given in the last column in table V(b). This distribution is given in figure 12 as operation A for 1,000 flight hours, landing speed of 70 knots, and 20° angle of dead rise.

APPENDIX B

ESTIMATES OF WAVE HEIGHTS

Considerable information is available on the conditions of the sea in the form of statistics on significant wave heights which designate the average height of the one-third highest wave heights. For many purposes, such as fatigue studies, more detailed information on wave heights is required. This appendix describes a method for using the data on significant wave heights to approximate the probability distribution of all wave heights.

The approach used in the following analysis can be divided into three steps: namely,

(a) Relating the significant wave height for a given sea condition to the root-mean-square value of the wave heights

(b) Determination of the distribution of the root-mean-square wave height from the distribution of the significant wave heights by means of step (a)

(c) Derivation of the probability distribution of all wave heights from the distribution of the root-mean-square wave height

In this paragraph, the relation between the significant wave height and the root-mean-square wave height is derived. The significant wave height H is defined as

$$H = 3\int_a^\infty hP(h)dh \tag{1}$$

where

h height of waves

P(h) probability distribution of wave heights for a given sea condition

and a is defined by the expression

$$\frac{1}{3} = \int_a^\infty P(h)dh \tag{2}$$

It is clear from equations (1) and (2) that H is the average value of the one-third highest waves. Before any further calculations can be made, it is necessary to specify the distribution of wave heights for a given sea condition $P(h)$. For present purposes, it will be assumed that $P(h)$ is given by

$$P(h) = \frac{2h}{\overline{h^2}} e^{-\frac{h^2}{\overline{h^2}}} \tag{3}$$

where $\overline{h^2}$ is the mean-square wave height. This distribution has been used with success in other investigations (ref. 11) to represent wave-height data and has a theoretical basis. Specifically, if the sea height is assumed to be a Gaussian disturbance with a narrow spectrum, it can be shown that the distribution of wave heights tends toward the distribution given by equation (3). Inasmuch as the sea height may generally be considered to have a narrow spectrum, this assumption appears reasonable. Substituting equation (3) into equations (2) and (1) successively yields the following results:

For the lower limit of integration of equation (2) for the significant wave height

$$a = 1.05\left(\overline{h^2}\right)^{1/2} \tag{4}$$

and

$$H = 1.41\left(\overline{h^2}\right)^{1/2} \tag{5}$$

Equation (5) may thus be used to convert measured values of H to their associated values of $\left(\overline{h^2}\right)^{1/2}$. It is also used directly to determine distributions of $\left(\overline{h^2}\right)^{1/2}$ from measured distributions of H, the distribution of $\left(\overline{h^2}\right)^{1/2}$ being given simply by the following relation:

$$f\left[\left(\overline{h^2}\right)^{1/2}\right] = 1.41f(H) \tag{6}$$

where $f(H)$ is the probability distribution of significant wave heights.

For a given sea condition defined by a value of significant wave height H or a value of root-mean-square wave height $\left(\overline{h^2}\right)^{1/2}$, the distribution of wave heights is given by equation (3) as

$$P(h) = \frac{2h}{\overline{h^2}} e^{-\frac{h^2}{\overline{h^2}}}$$

The proportion of waves exceeding a given height for this case is then given by

$$P^*(h) = e^{-\frac{h^2}{\overline{h^2}}} \tag{7}$$

If the quantity $\overline{h^2}$ varies from day to day or location and, therefore, must also be described by a probability distribution, the overall proportion of wave heights exceeding a given value is then given by

$$Q(h) = \int_0^\infty e^{-\frac{h^2}{\overline{h^2}}} f\left[\left(\overline{h^2}\right)^{1/2}\right] d\left(\overline{h^2}\right)^{1/2} \tag{8}$$

where $f\left[\left(\overline{h^2}\right)^{1/2}\right]$ is the distribution of root-mean-square wave height. Thus, converting distributions of significant wave height to overall distributions of wave height consists of two steps:

(1) Application of equation (6) to determine the distribution of $\left(\overline{h^2}\right)^{1/2}$ from distributions of significant wave heights H

(2) Application of resultant distribution of $f\left[\left(\overline{h^2}\right)^{1/2}\right]$ in equation (8)

In order to illustrate the application of the foregoing procedure, it is assumed that the significant wave height has the following distribution:

$$f(H) = \frac{2H}{\overline{H^2}} e^{-\frac{H^2}{\overline{H^2}}} \tag{9}$$

This distribution was used in reference 11 in this connection and was found to approximate some available data on significant wave heights. However, it may not have a general application. It is, by coincidence, the same distribution assumed earlier to apply to distributions of wave height $P(h)$ for a given sea condition. The data of reference 11, for example, also give a mean-square value of wave height $\overline{H^2}$ of 60 for data for the open sea. Substituting values of $\overline{H}$, $\overline{H^2}$, and $f(H)$ derived from equations (5) and (6) into equation (9) yields the following distribution for $\left(\overline{h^2}\right)^{1/2}$, where the simpler notation of y is substituted for $\left(\overline{h^2}\right)^{1/2}$:

$$f(y) = \frac{2y}{\overline{y^2}} e^{-\frac{y^2}{\overline{y^2}}} \tag{10}$$

Substituting equation (10) into equation (8) yields the final result for the overall distribution of peaks exceeding given values of h

$$Q(h) = \int_0^\infty \frac{2y}{\overline{y^2}} e^{-\frac{h^2}{y^2}-\frac{y^2}{\overline{y^2}}} dy \tag{11}$$

where it may in turn be shown from equation (5) that

$$\overline{y^2} = \frac{\overline{H^2}}{(1.41)^2}$$

Evaluations of the integrals defined by equations (8) and (11) have been performed and form the basis for the derived data on distributions of wave height in figure 9.

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TABLE I.- HEIGHT, LENGTH, AND PROPAGATION VELOCITY OF WAVES

(a) Wave length, λ, ft

h/λ	Values of h of -							
	1	3	5	7	10	20	30	40
1/20	20	60	100	140	200	400	600	800
1/30					300	600	900	1,200
1/40	40	120	200	280	400	800		
1/50					500			
1/60	60	180	300	420				
1/80	80	240						
1/100	100							

(b) Wave propagation velocity, c, knots

h/λ	Values of h of -							
	1	3	5	7	10	20	30	40
1/20	5.9	10.4	13.4	15.9	19.0	26.9	32.8	38.0
1/30					23.2	32.8	40.2	46.5
1/40	8.5	14.7	19.0	22.4	26.9	38.0		
1/50					29.8			
1/60	10.4	18.0	23.2	27.4				
1/80	12.0	20.8						
1/100	13.4							

TABLE II.- ASSUMED OPERATIONS

Airplane	Speed, knots	Angle of dead rise, deg	Length of mission, hr	Sea condition
Patrol bomber (Operation A)	70 and 120	20 and 40	11	25 percent, sheltered area 25 percent, lee side of island 50 percent, open ocean
Patrol bomber (Operation B)	70 and 120	20 and 40	11	65 percent, sheltered area 25 percent, lee side of island 10 percent, open ocean
Supersonic bomber (Operation C)	70 and 120	20 and 40	9	50 percent, sheltered area 49 percent, lee side of island 1 percent, open ocean
Supersonic bomber (Operation D)	70 and 120	20 and 40	9	50 percent, sheltered area 49.99 percent, lee side of island .01 percent, open ocean
Antisubmarine warfare (Operation E)	40 and 80	20 and 40	5	10 percent, sheltered area 90 percent, open ocean

TABLE III.- COMPUTATION OF DISTRIBUTION OF WAVE HEIGHTS

Wave height, ft	Probability			0.25 × (1)	0.25 × (2)	0.50 × (3)	(4)+(5)+(6)
	Sheltered area (1)	Lee side of island (2)	Open ocean (3)	(4)	(5)	(6)	(7)
0	1.00	1.00	1.00	0.25	0.25	0.50	1.000
2	.082	.24	.61	.0205	.06	.305	.386
4	.0076	.067	.35	.0019	.017	.175	.194
6	.0008	.02	.19	.0002	.005	.095	.100
8	.000095	.0066	.10	.000024	.00165	.05	.052
10	.000012	.0022	.056	.000003	.00055	.028	.0286
12	.0000018	.00078	.033	.00000045	.000195	.0165	.0167
14	.0000004	.00026	.020	.0000001	.000065	.01	.01
16		.0001	.013		.000025	.0065	.0065
18		.00004	.0086		.00001	.0043	.0043
20		.000015	.0057		.0000037	.00285	.00285
22		.000006	.0039		.0000015	.00195	.00195
24		.0000023	.0026		.00000057	.0013	.0013
26		.000001	.0018		.00000025	.0009	.0009
28			.0012			.0006	.0006
30			.0009			.00045	.00045
32			.00063			.000315	.000315
34			.00045			.000225	.000225
36			.00032			.00016	.00016
38			.00023			.000115	.000115
40			.00016			.00008	.00008

TABLE IV.- PROPORTION OF WAVES OF GIVEN HEIGHTS

Wave height, ft	Probability (1)	Frequency (2)	Wave height, ft (3)	Mean wave height, ft (4)
0	1.00	0.725	0 to 3	2
3	.275	.14	3 to 5	4
5	.135	.065	5 to 7	6
7	.07	.033	7 to 9	8
9	.037	.020	9 to 12	10
12	.017	.0115	12 to 17.5	15
17.5	.0055	.00443	17.5 to 25	20
25	.00107	.00089	25 to 35	30
35	.00018	.00018	35 to -	40

TABLE V.- COMPUTATION OF DISTRIBUTION OF ACCELERATIONS FOR AN ASSUMED OPERATION

(a) Probability of exceeding given acceleration by wave height with 100 percent operation assumed for each wave height

n, g units	Wave height, ft								
	2 (1)	4 (2)	6 (3)	8 (4)	10 (5)	15 (6)	20 (7)	30 (8)	40 (9)
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	.58	.65	.70	.72	.74	.76	.78	.80	.82
2	.24	.30	.35	.38	.41	.44	.48	.52	.54
3	.069	.117	.154	.18	.20	.232	.27	.306	.33
4	.018	.040	.062	.082	.094	.12	.146	.176	.196
5	.0039	.013	.022	.032	.039	.054	.073	.093	.11
6		.0039	.0072	.012	.015	.024	.034	.046	.059
7			.0022	.004	.0054	.0096	.015	.022	.029
8				.0012	.0019	.0038	.0064	.01	.014
9						.0014	.0026	.0043	.0064
10							.001	.0018	.0029
11									.0012

(b) Probability of exceeding given acceleration by wave height for percentage of assumed operation in each wave height

n, g units	Wave height, ft										
	2 (1) × 0.725	4 (2) × 0.14	6 (3) × 0.065	8 (4) × 0.033	10 (5) × 0.020	15 (6) × 0.0115	20 (7) × 0.00443	30 (8) × 0.00089	40 (9) × 0.00018	Sum of probabilities (10)	(10) × 7,414
0	0.725	0.14	0.065	0.033	0.020	0.0115	0.00443	0.00089	0.00018	1.000000	7,414
1	.4205	.091	.0455	.02376	.0148	.00874	.003455	$.712 \times 10^{-3}$	$.148 \times 10^{-3}$	.6086	4,510
2	.174	.042	.02275	.01254	.0082	.00506	.00213	.463	.0972	.2672	1,982
3	.050025	.0164	.01001	.00594	.0040	.002668	.00120	.272	.0594	.0906	573
4	.01305	.0056	.00403	.002706	.00188	.00138	.000647	.157	.0353	.0295	219
5	.002828	.00182	.00143	.001056	.00078	.000621	.000323	.0828	.0198	.00896	66.5
6		.000546	.000468	.000396	.0003	.000276	.000151	.0409	.0106	.00219	16.3
7			.000143	.000132	.000108	.0001104	.0000665	.0196	.00522	.000585	4.3
8				.0000396	.000038	.0000437	.0000284	.0089	.00252	.000161	1.2
9						.0000161	.0000115	.00383	.00115	.0000326	.24
10							.00000443	.00160	.000522	.00000655	.048
11									.000216	.000000216	

TABLE VI.- COMPUTATION OF NUMBER OF IMPACTS FOR AN ASSUMED OPERATION

Wave height, ft	Total distance traveled × probability of wave height (1)	Average wave length, ft (2)	Number of waves or impacts (3)
0 to 3	660,000	105	6,290
3 to 5	127,000	180	706
5 to 7	59,100	240	248
7 to 9	30,000	320	94
9 to 12.5	18,100	400	45
12.5 to 17.5	10,500	480	22
17.5 to 25	4,400	550	8
25 to 35	800	750	1
35 to -	100	1,000	
Totals	910,000	-----	7,414

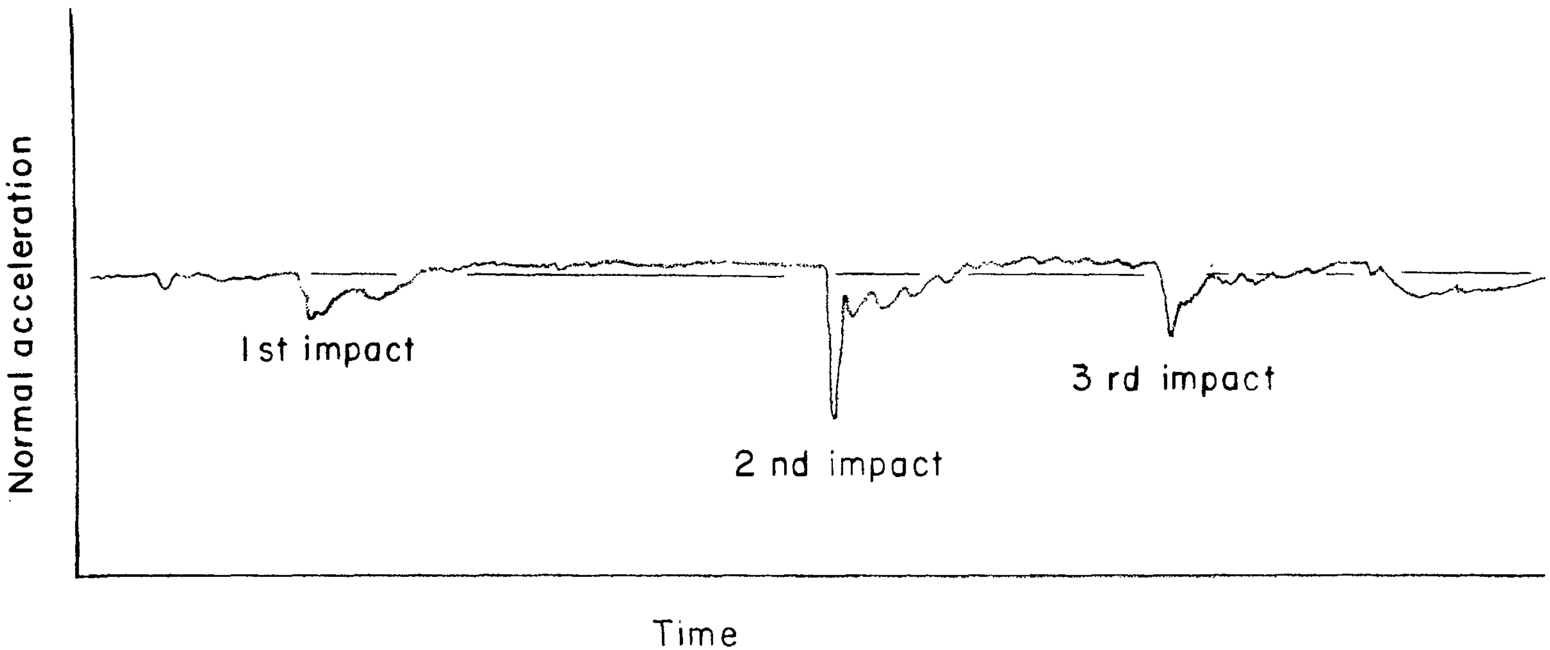
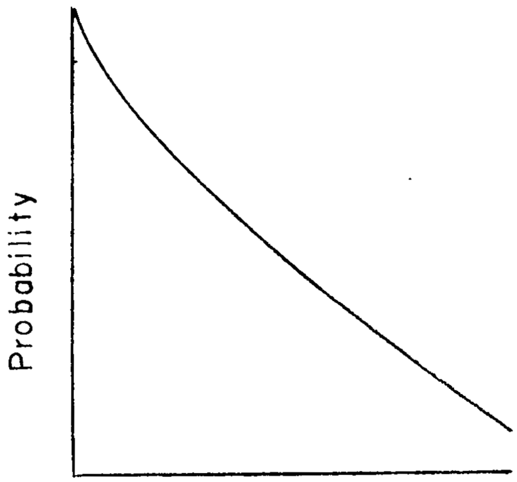
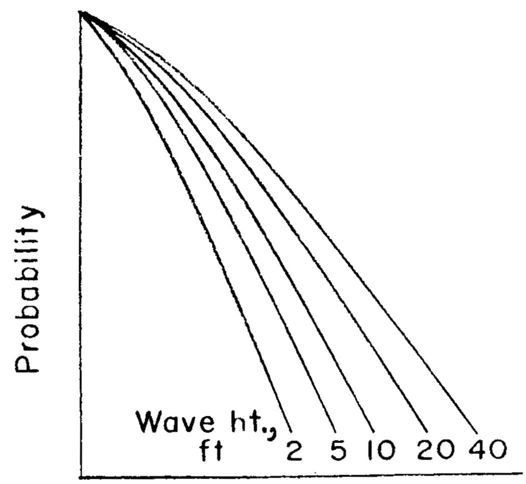


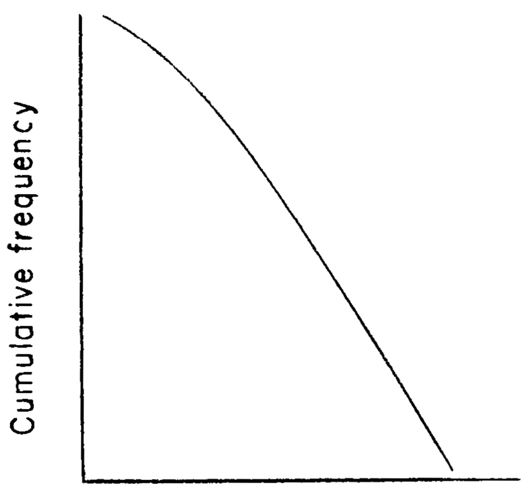
Figure 1.- Tracing of time history of normal acceleration for landing of model in 4-foot waves.



(a) Wave height.



(b) Acceleration.



(c) Acceleration.

Figure 2.- Three basic elements for estimating the load for a seaplane.

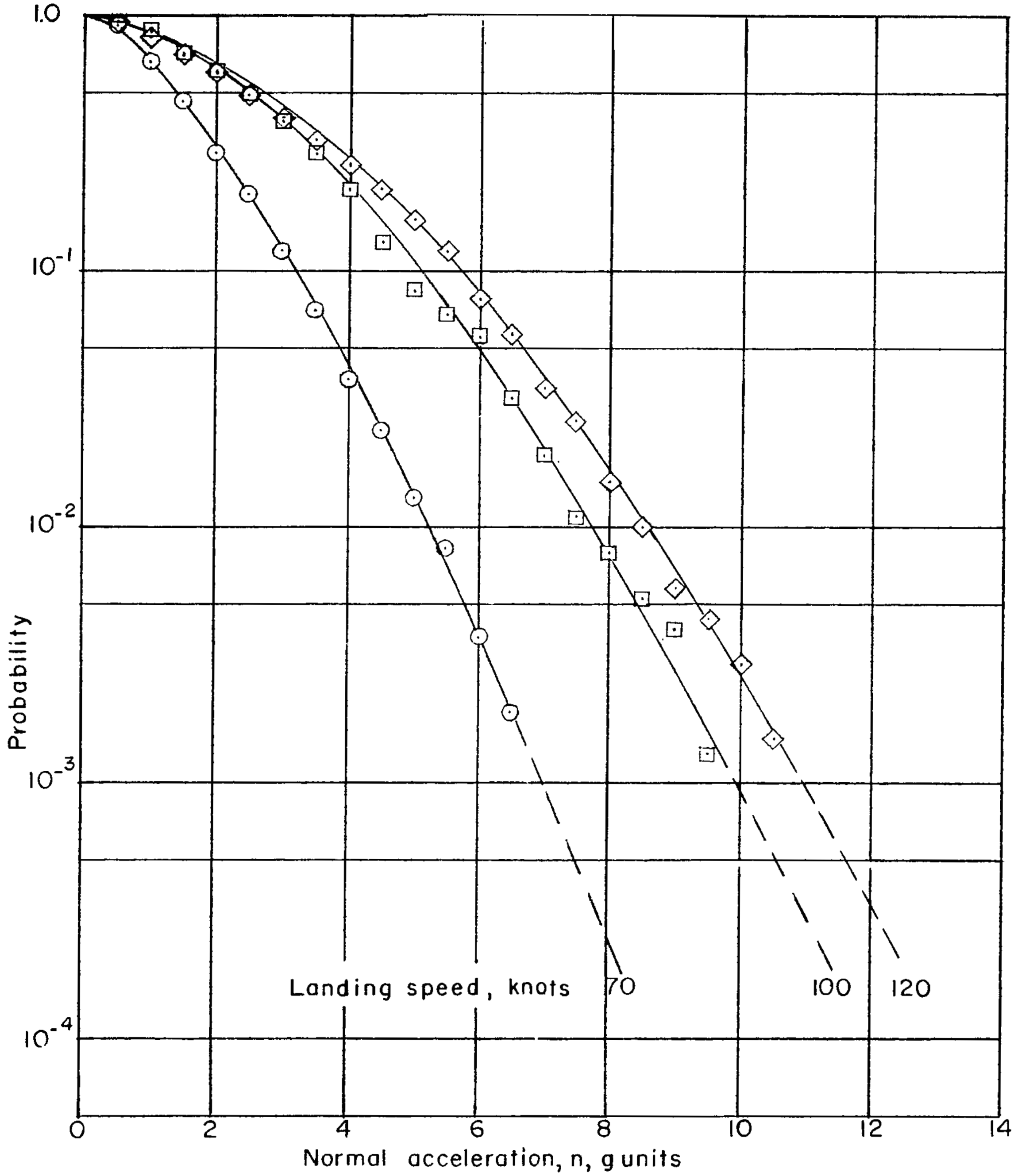


Figure 3.- Probability of exceeding given normal accelerations for three different landing speeds. (Data from models A, B, and C.)

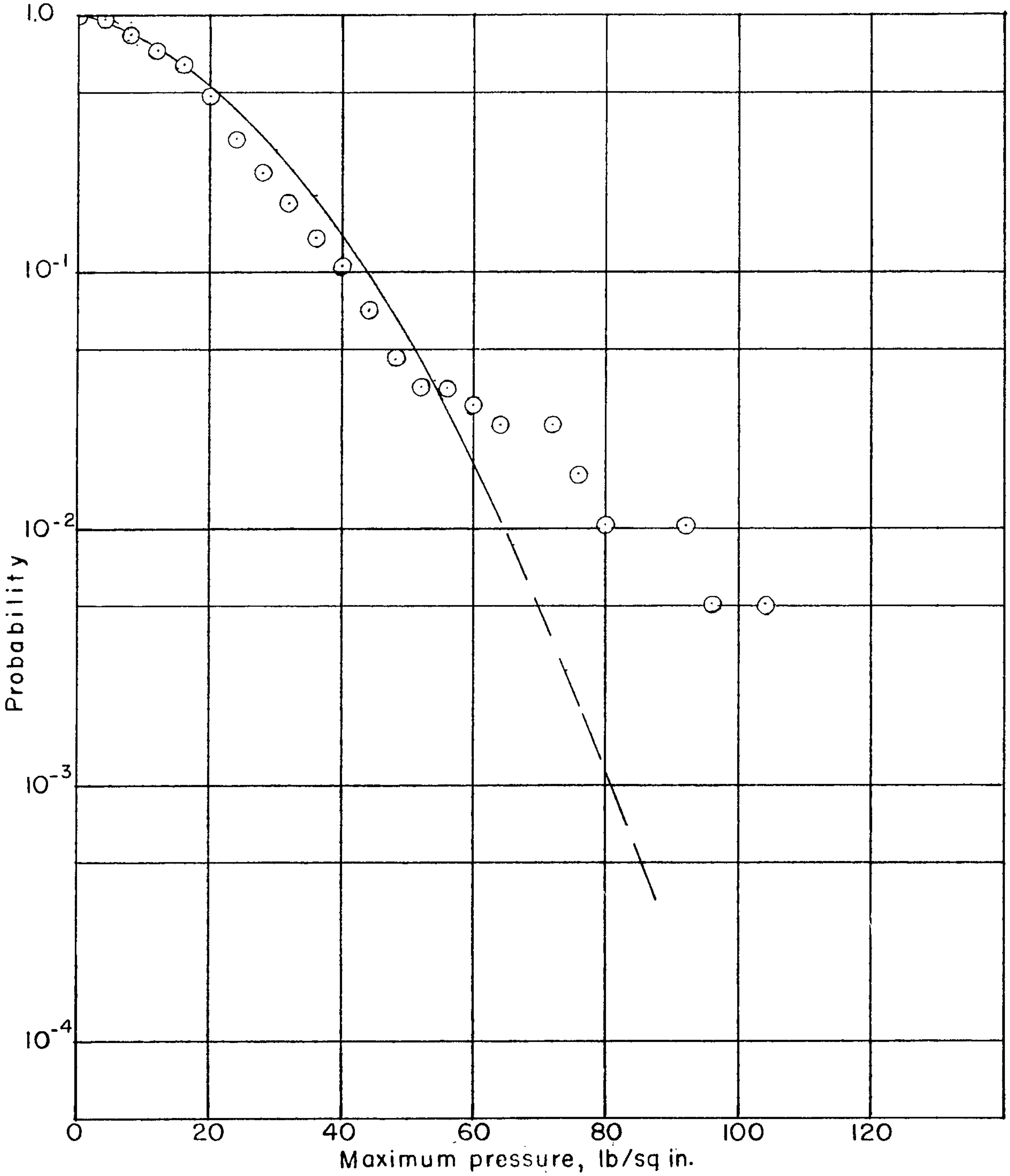


Figure 4.- Probability of exceeding given maximum pressures near step of full-scale seaplane landing in approximately 2-foot waves.

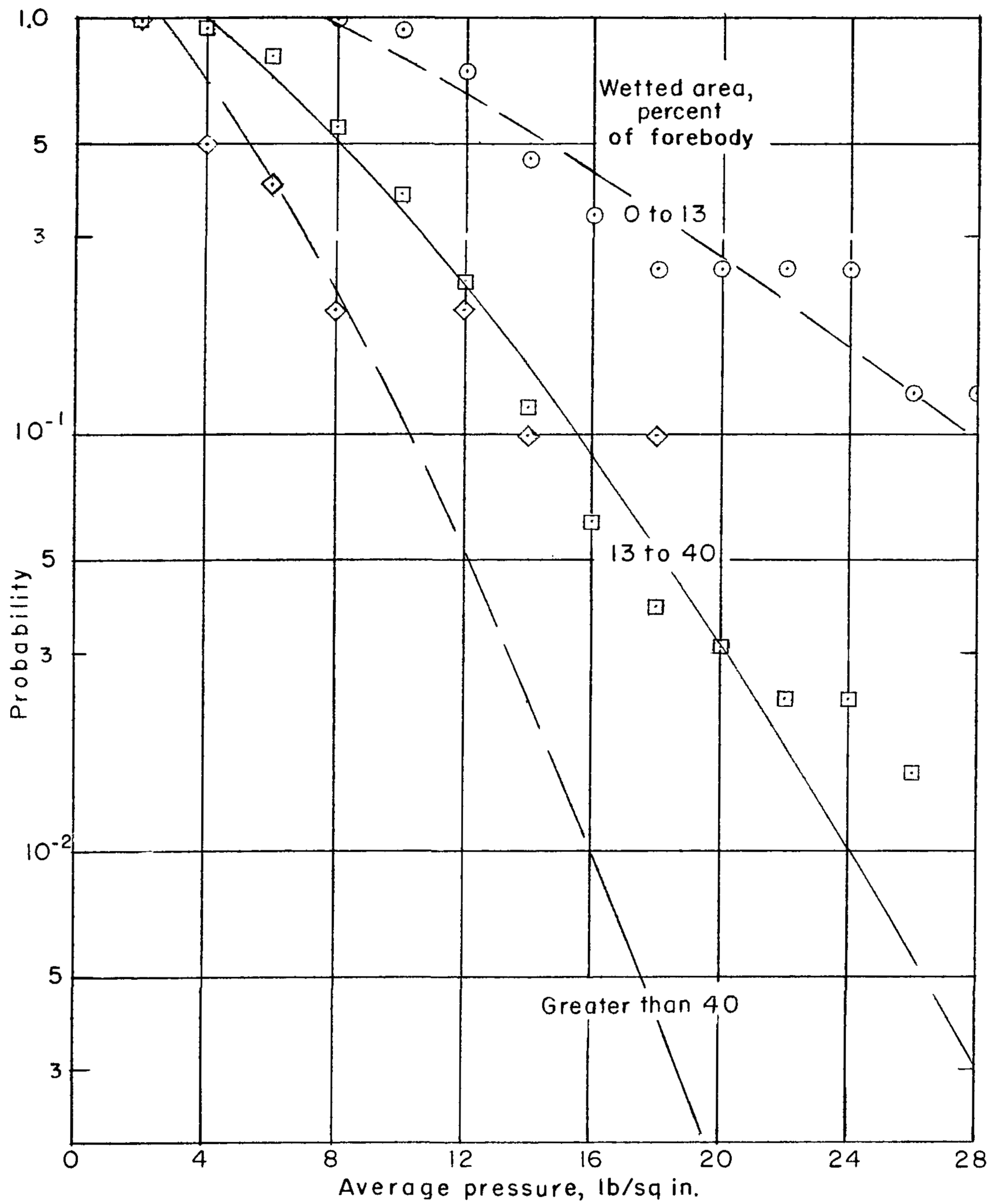


Figure 5.- Probability of exceeding given average pressure on full-scale seaplane for different values of wetted area.

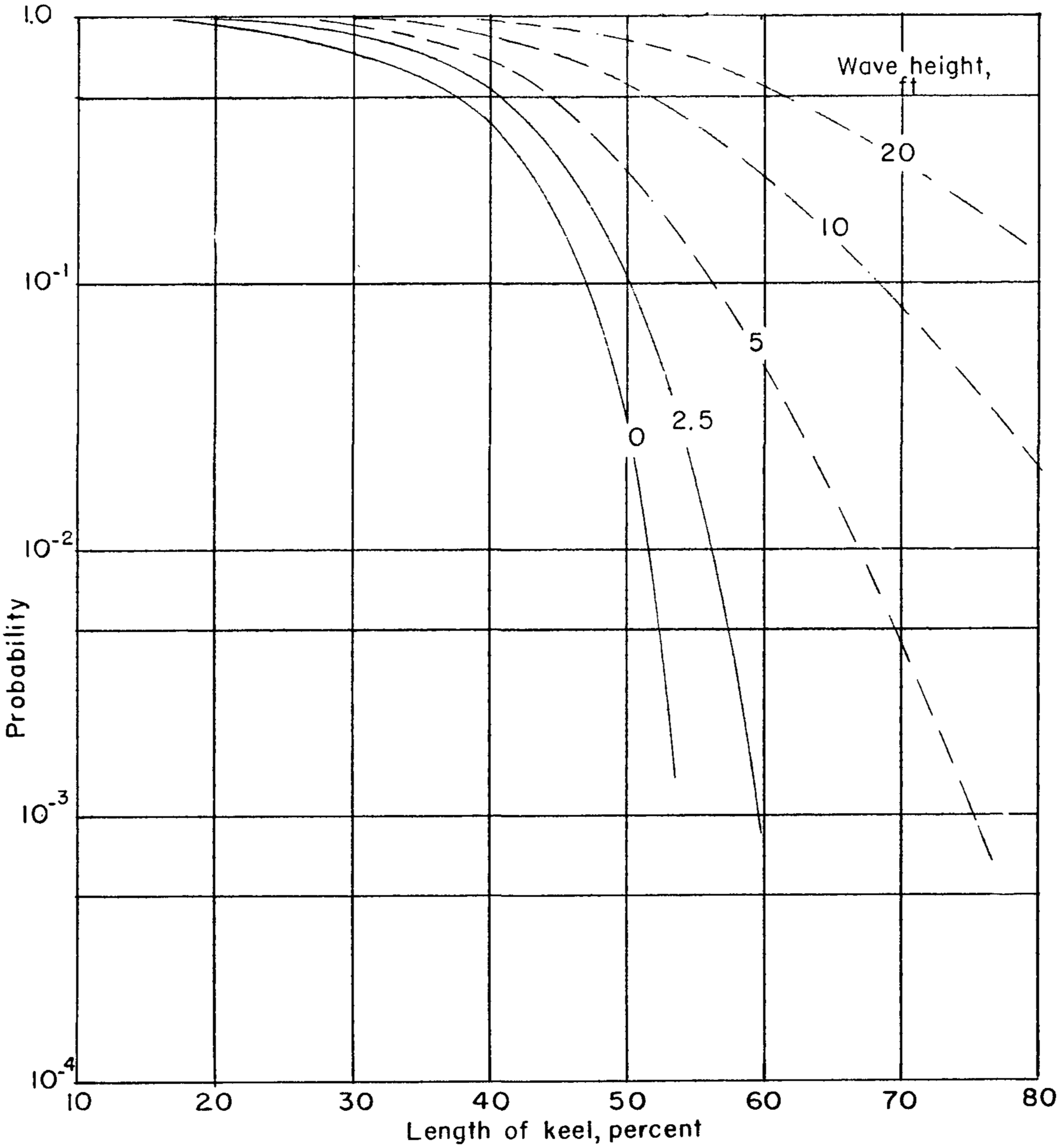


Figure 6.- Probability of exceeding given wetted keel lengths on full-scale seaplane for different wave heights.

[redacted]

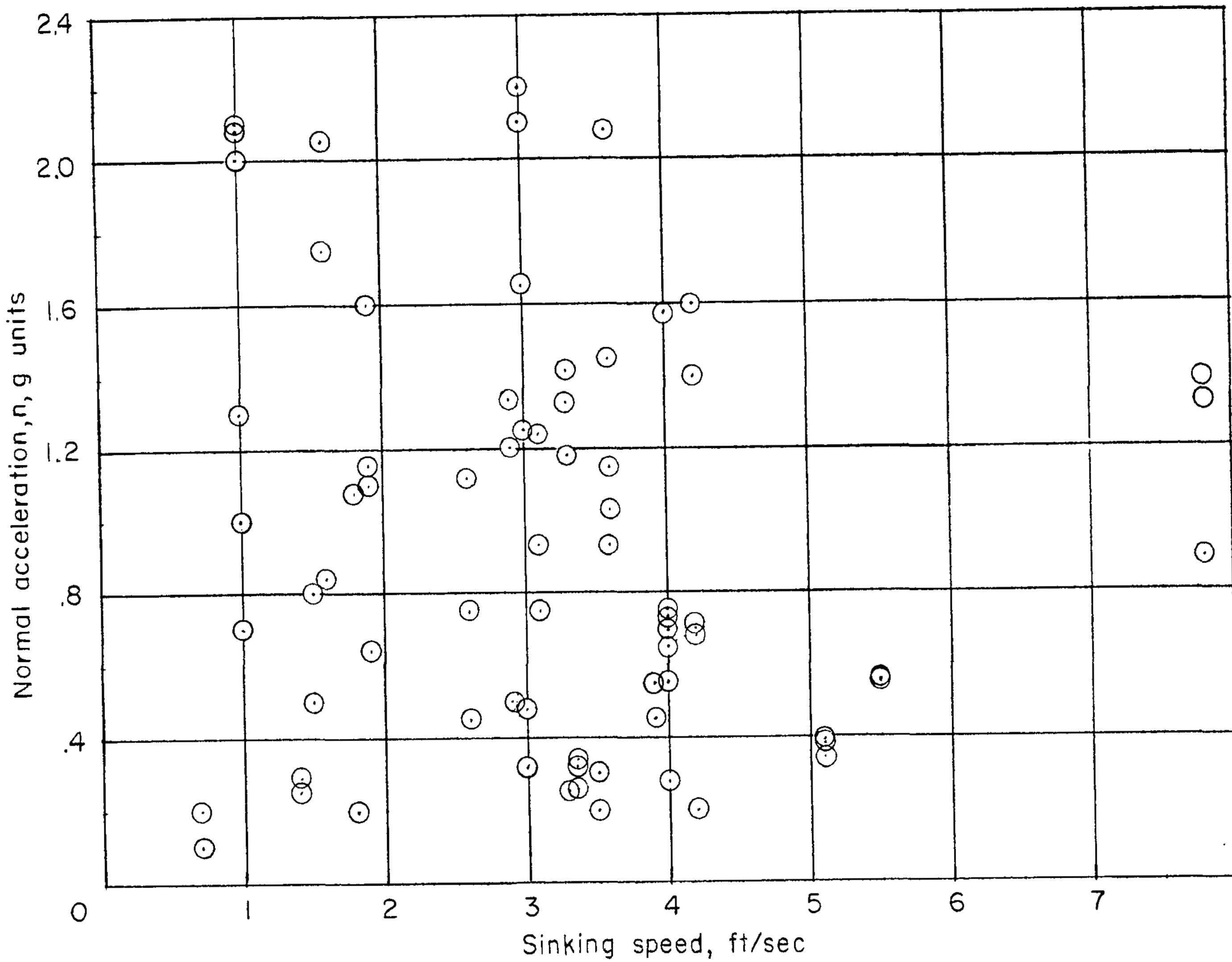


Figure 7.- Variation of normal acceleration with sinking speed at impact for full-scale seaplane.

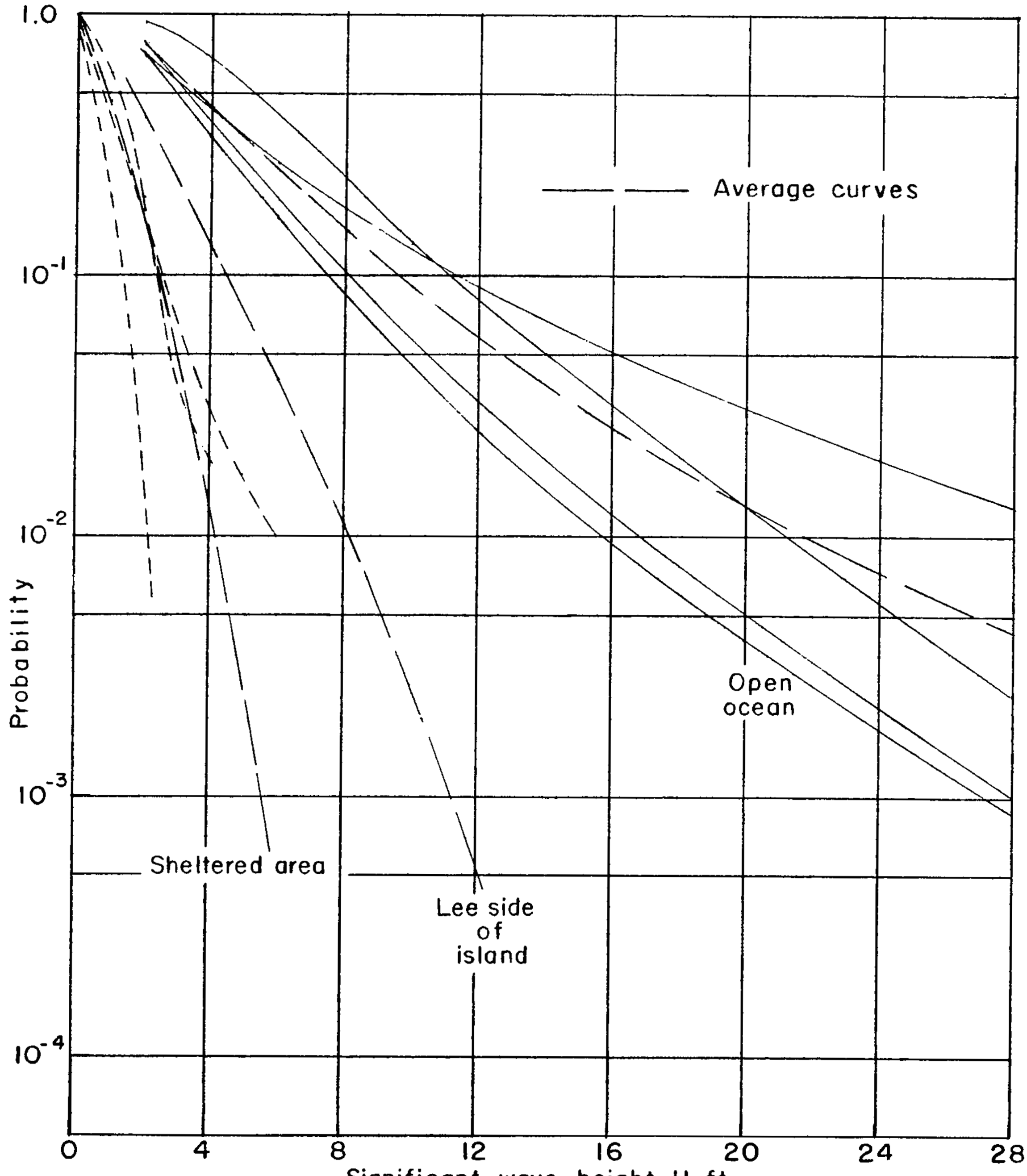


Figure 8.- Distributions of significant wave heights for several areas.

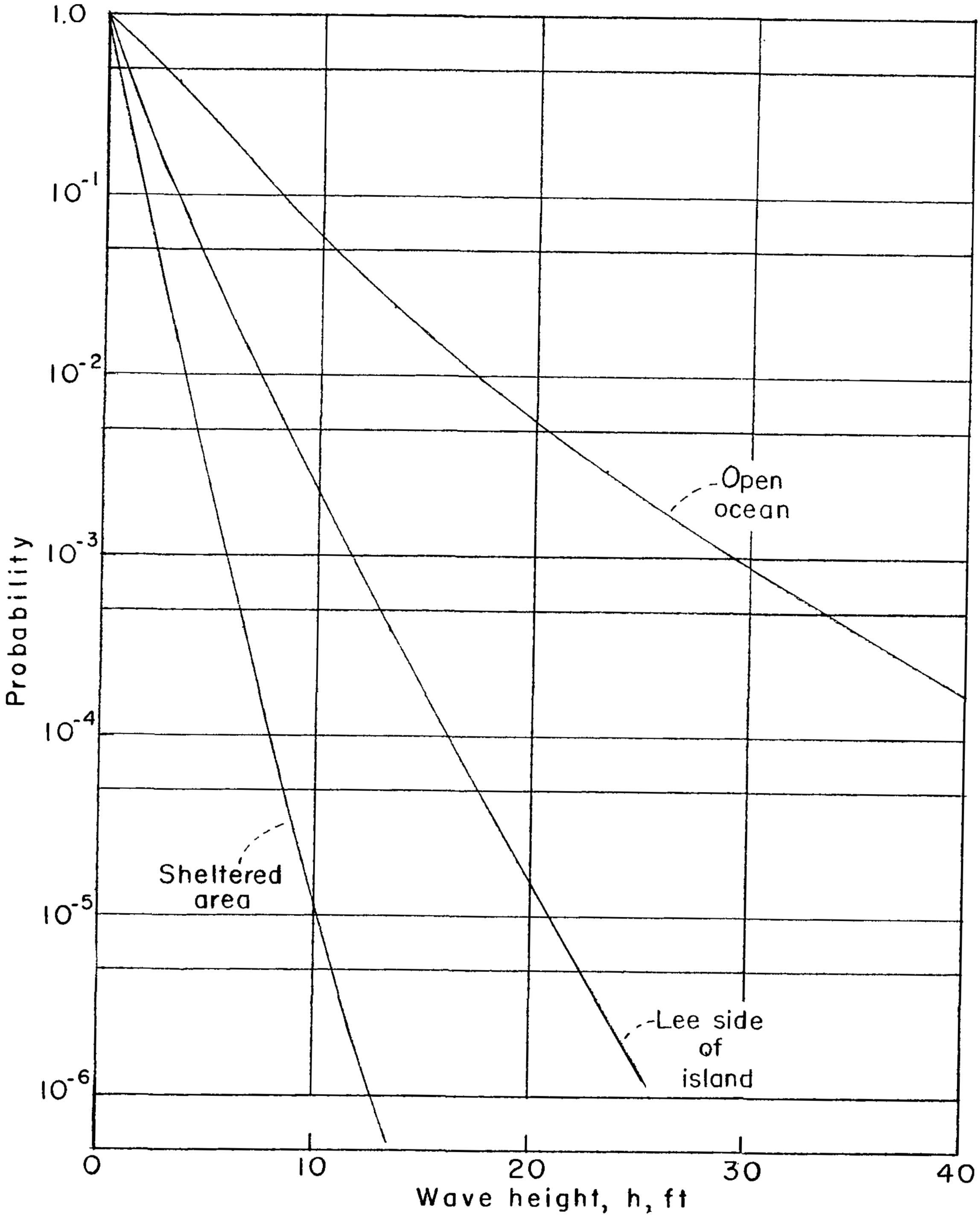


Figure 9.- Average distributions of wave heights.

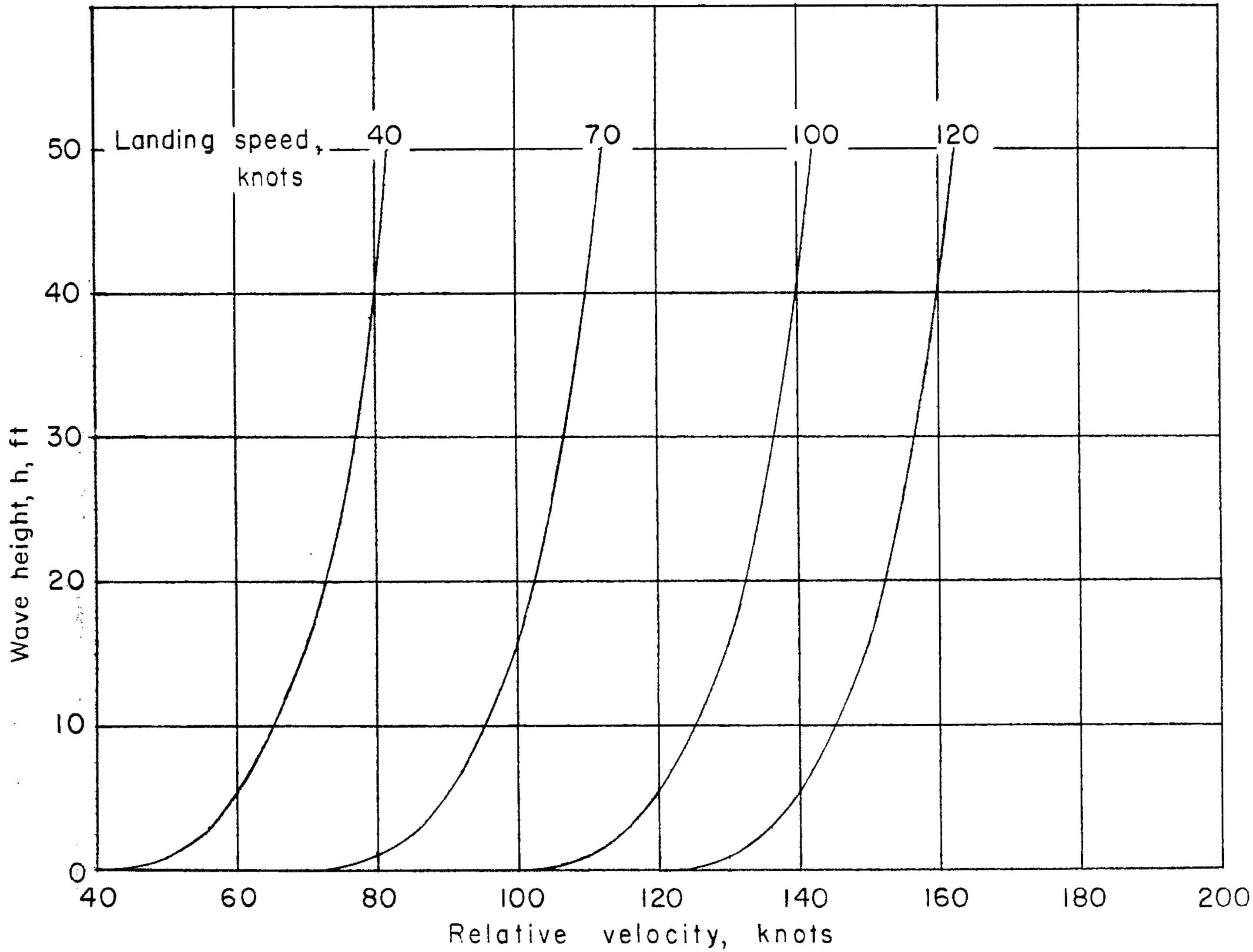


Figure 10.- Relative velocity of seaplane and wave propagation velocity for four landing speeds.

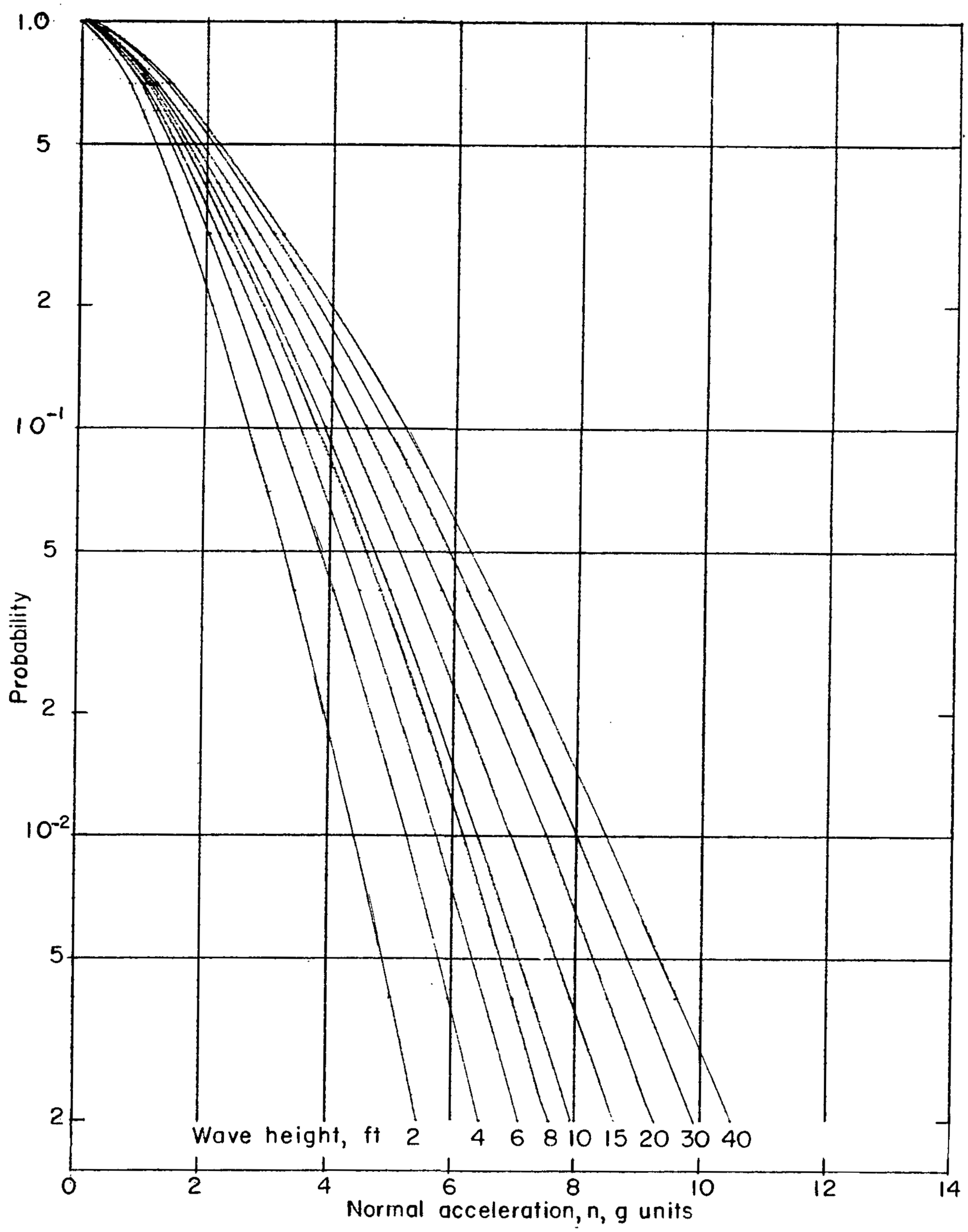


Figure 11.- Distribution of normal acceleration for landings in constant wave heights.

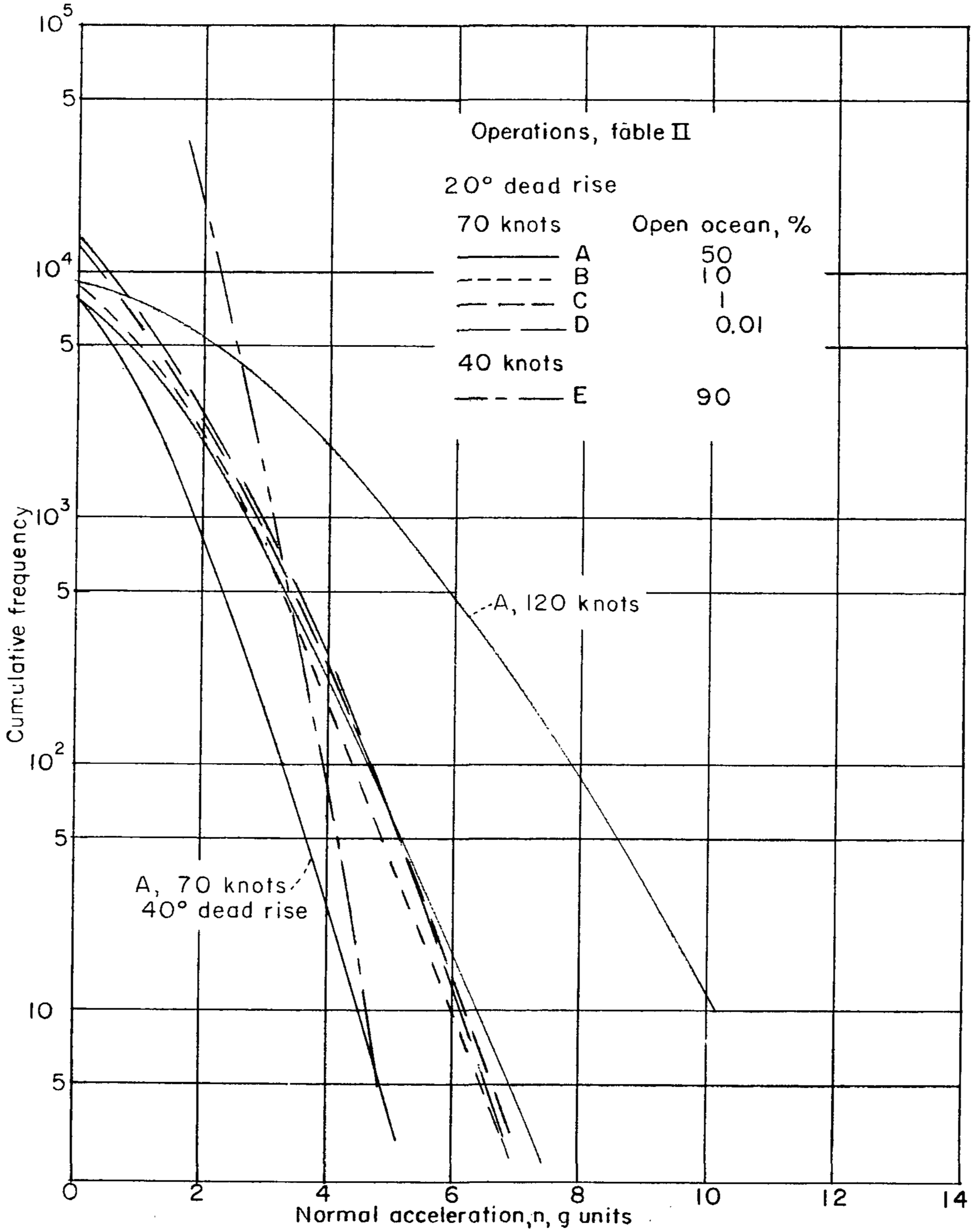


Figure 12.- Frequency of exceeding given acceleration in 1,000 flight hours for seven operations.

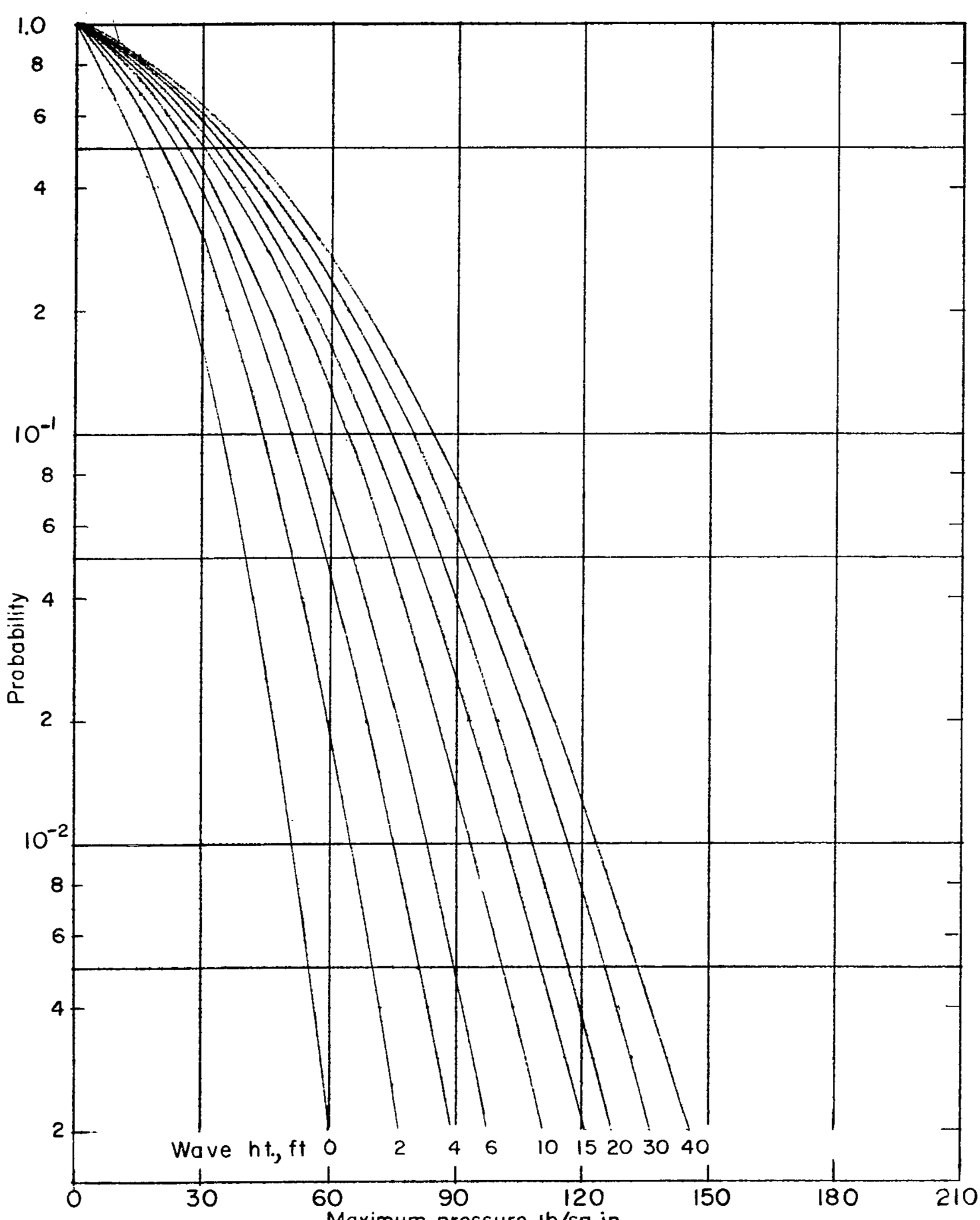


Figure 13.- Distribution of maximum pressures for landings in constant wave heights.

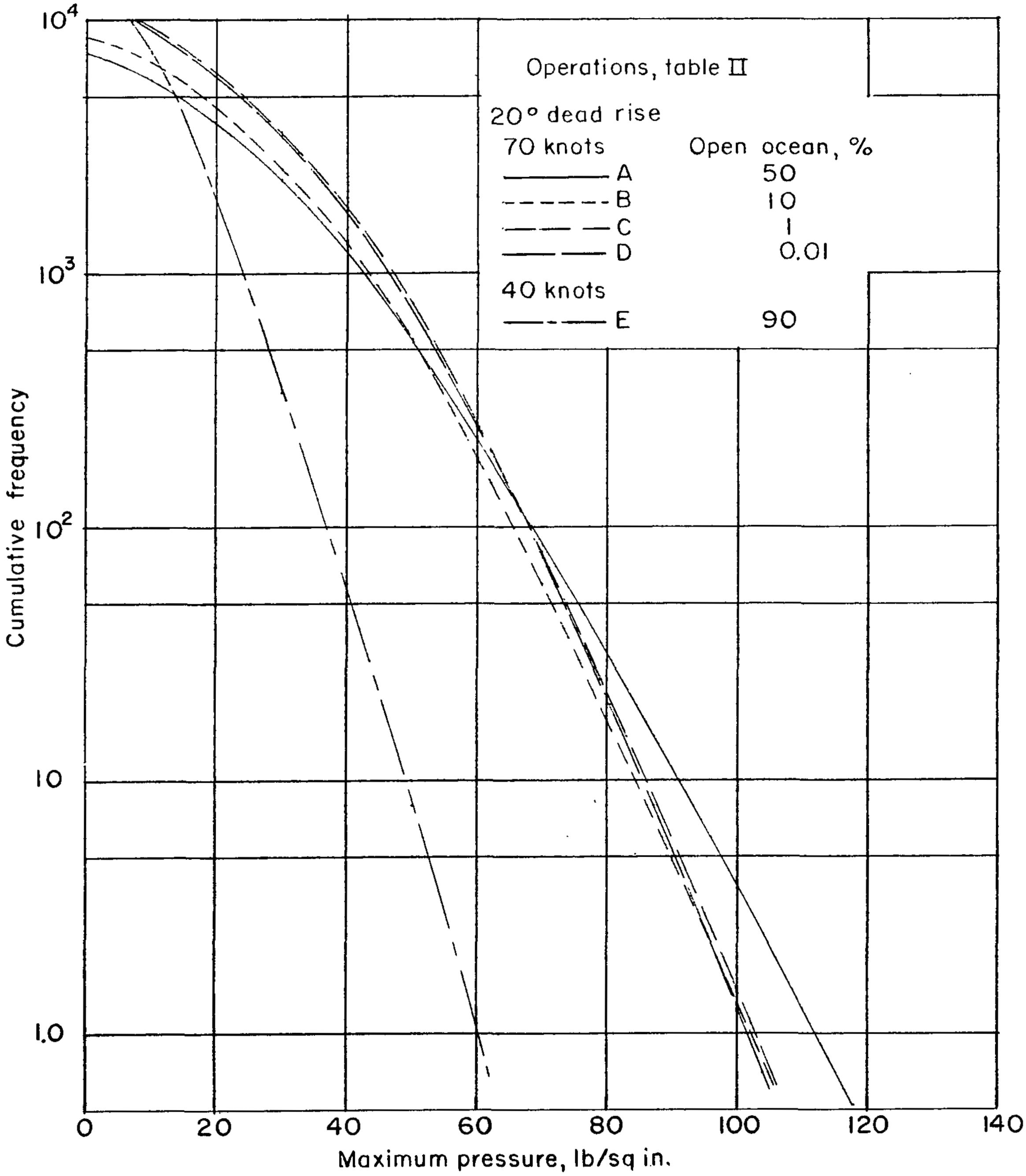


Figure 14.- Frequency of exceeding given maximum pressures at step in 1,000 flight hours for five operations.

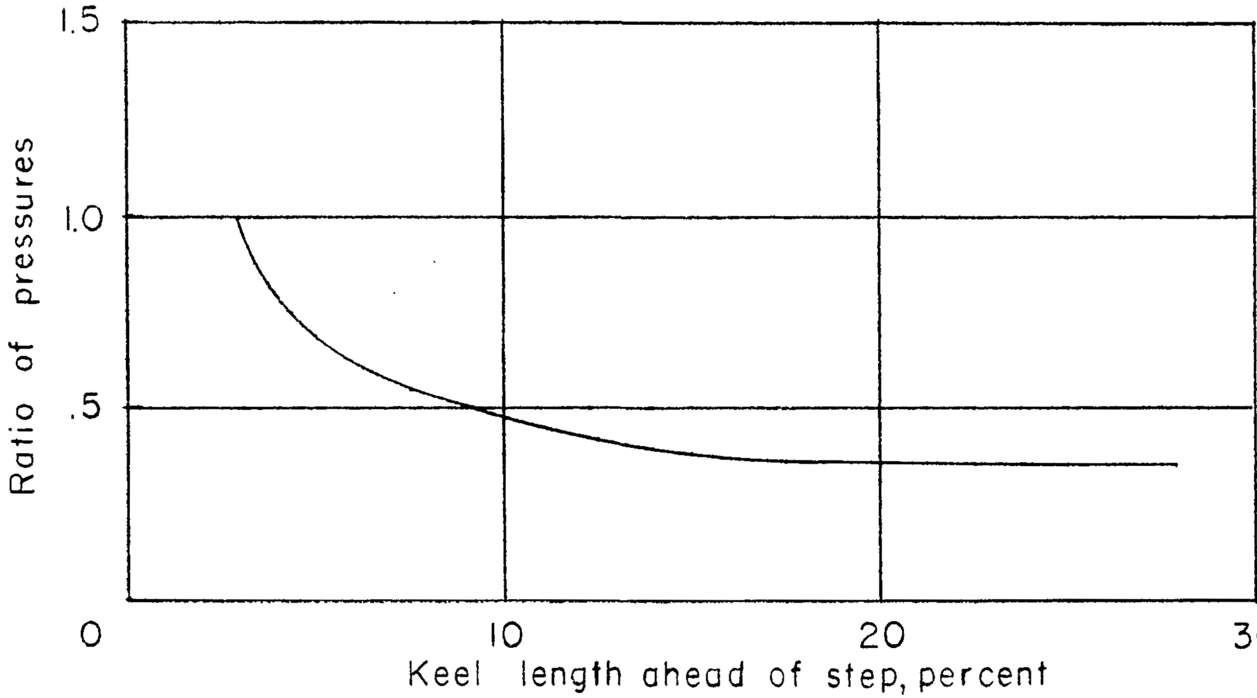


Figure 15.- Ratio of maximum pressure to maximum pressure at step as wetted area moves forward.

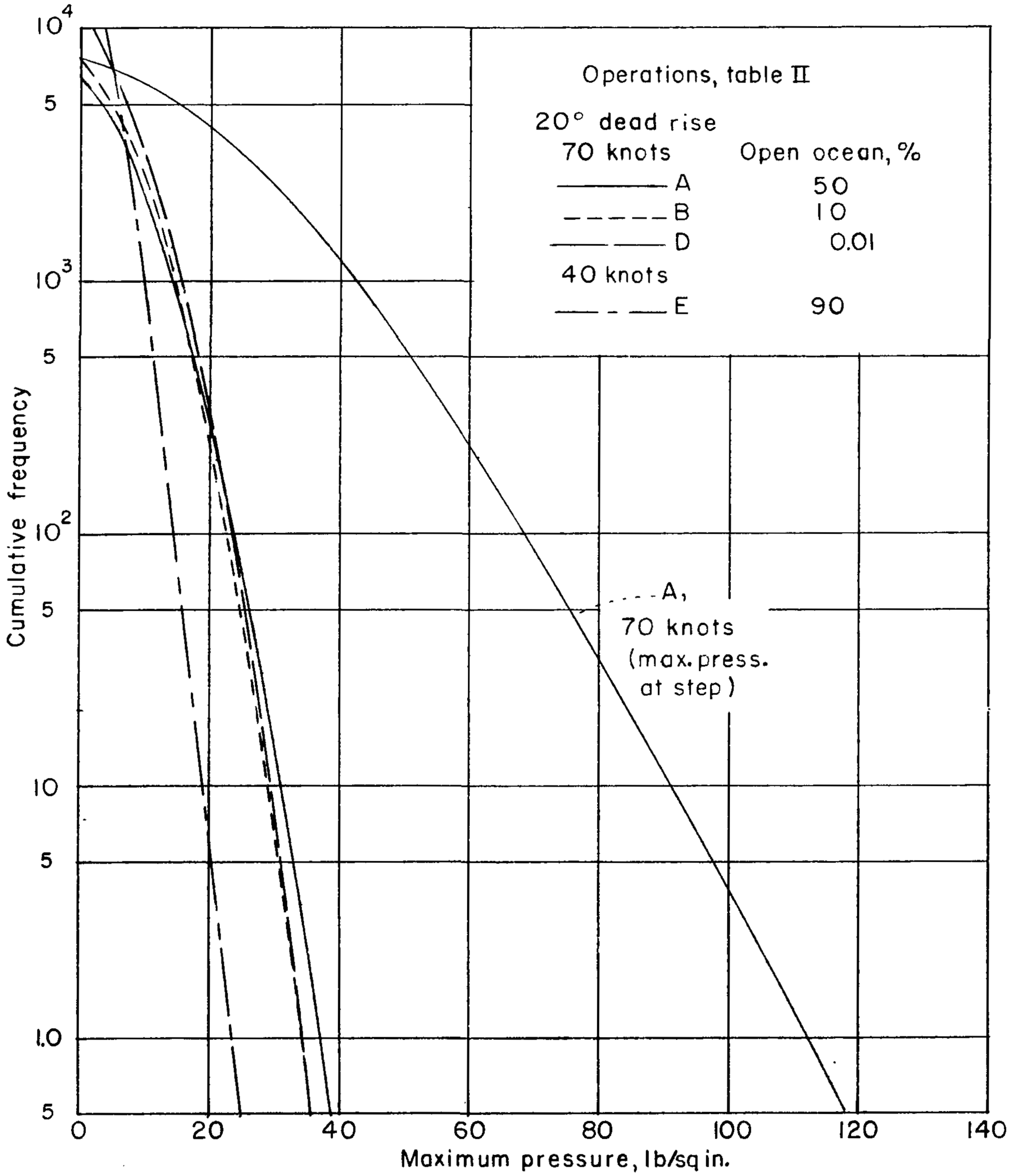


Figure 16.- Frequency of exceeding given maximum pressures at 25 percent keel length in 1,000 flight hours.

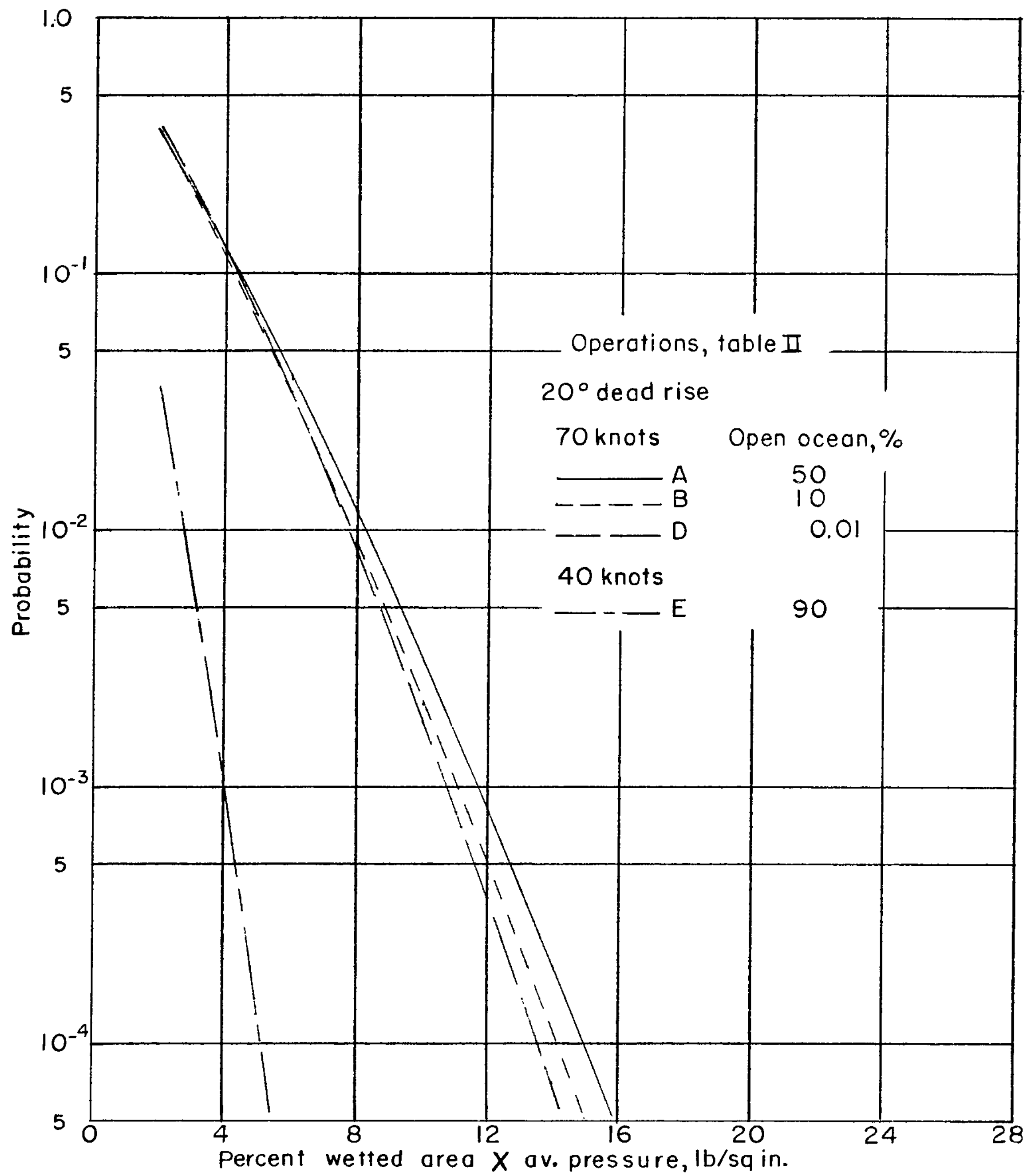


Figure 17.- Probability of exceeding given total pressures in 1,000 flight hours.

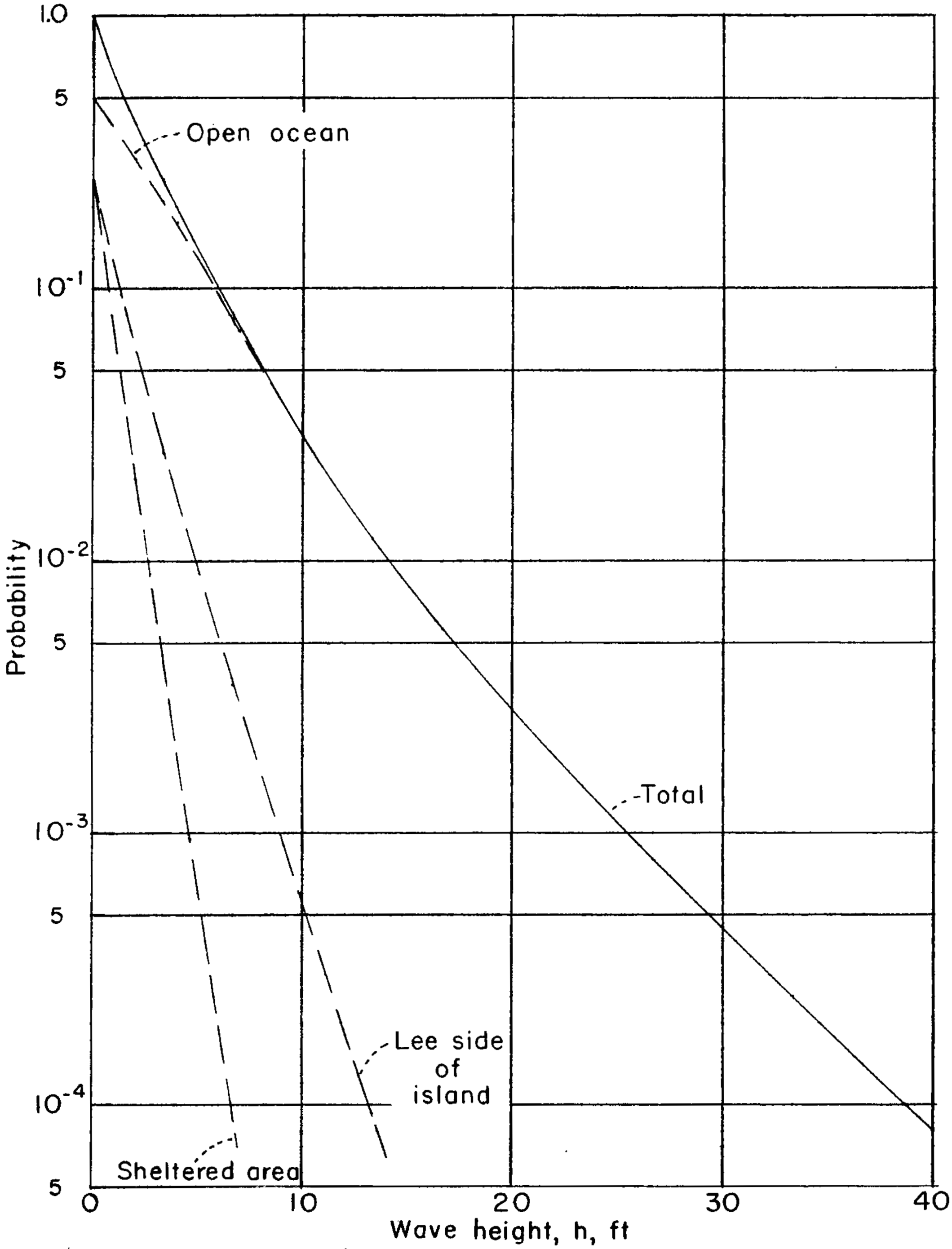


Figure 18.- Total distribution of wave heights with contributing distributions for operation A.

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